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Review

Longevity and sustainability of tropical and subtropical restored seagrass beds among Atlantic, Pacific, and Indian Oceans

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ABSTRACT

Seagrass longevity up to 47 years in well-restored, well-sited seagrass restorations are demonstrated from 253 trials at 83 regional sites in tropical and subtropical portions of three oceans (Atlantic, Pacific, Indian Oceans). These trials include over 3.04 million planted units into 306.3 ha. Approximately 12% of the total global tropical restored seagrass by Van Katwijk, Thorhaug et al. (2016) calculations from 1786 trials are included. Almost all projects herein reviewed persisted since date of planting except several cases with harsh anthropogenic impact or forceful natural events in first post-planting months. The oldest tropical/subtropical restoration continually observed is 47 yrs, many are 35 yrs. An array of observed and/or measured restored services accompanied these. This review may provide informational background for government resource managers, legislators, scientists, and citizens concerning tropical/subtropical seagrass longevity. This data from these trials may substantiate future seagrass restoration investments. Public outreach, national & regional government training,and outreach occurred, needing continuation.

1. Introduction

The important near shore resource of seagrass has not been well managed by tropical/subtropical nations globally. Presently, the accelerating seagrass loss is estimated at 7% per year, with 51,000 km^2 decimated (Waycott et al., 2009) from a total of 171,000 km^2. Along with preservation seagrass will need to be restored. An objective global analysis of 1786 seagrass restoration trials (Van Katwijk et al., 2016) found larger-scale seagrass restoration more successful than smaller trials. This objective global analysis demonstrated seagrass restoration as a viable technique for stemming the tide of seagrass loss globally. An important question remaining unanswered from the Van Katwijk et al. (2016) review was whether restored seagrass beds persisted over long periods or whether seagrass had age limitations as did mangrove tree restoration. Longevity information was lacking chiefly due to an absence of long-term monitoring data provided by the individual investigators participating in the 2016 analysis since the majority of investigators' 1786 trials were not monitored beyond 24–36 months.

Of the 1786 seagrass revegetation plantings around the globe, totaling approximately 26.1 km^2, there were fewer restoration efforts in the tropics than in the temperate zone (Van Katwijk et al., 2016).The tropical foundation species of seagrass have been best previously

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identified as already stressed, a concept has been applied to tropical species generally being more fragile than temperate species (Moore, 1958, 1972; Thorhaug, 1977, Eklöf et al., 2005). The Van Katwijk et al. (2016) review found that more than half of the total global seagrass restoration efforts were carried out in the temperate zone with one single genera *Zostera marina (*although additional genera in temperate zone were also restored). The majority of the *Zostera* restoration utilized a totally different methodology from most other restoration trials. *Zostera* produces a hard seed type, capable of being stored for long periods and then dispersed in a variety of methods such as casting in bulk from a vessel. With casting, no precise location of the *Zostera* PU (planting units) success is possible, thus no precise follow-up re-locating each of the PU as occurred in tropical species planting. Therefore, no exact age could be attached to a restoration effort. Using a variety of different methodologies but all having large fixed PU's, the results herein reviewed for subtropical and tropical species are planted by plugs, sprigs, or very large cultivated seedlings they have been individually planted *(Enhalus, Thalassia*). All of which can be precisely relocated, monitored and then followed by observation. However, only a few of the existing seagrass projects in various parts of the tropical to the sub-tropical world in Asia, Africa, and the Western Hemisphere have continually observed their tropical/subtropical seagrass restorations over time. We review four subtropical to tropical large-scale projects sites which were continually observed in Pacific (Australia and Indonesia) and Atlantic (Florida, Jamaica) Oceans. Then, we focus on a fifth example with multiple sites extending from subtropics to upper tropics over the entire Texas coastline carried out by the present authors. Texas seagrass restoration data is monitored in detail for 5–6 years for Texas government requirement after which the two principle investigators' (Belaire and Thorhaug) observations continued over many years. This Texas example additionally provides an excellent stewardship example for resource management when an entire region pivots from an accelerating loss pattern to activities gauged to bolster seagrass extent.

We note above that by far the best-financed seagrass restoration is the temperate *Zostera* restoration by Orth et al. (2006, 2010) utilizing chiefly small, hard seeds[1] of *Zostera marina,* a dominant temperate seagrass (Van Katwijk et al., 2016). Although this project has demonstrated sustainability since the 1980's, this *Zostera* project does not shed much light on the differing tropical/subtropical species sustainability.

Much seagrass loss has occurred in tropical newly-industrializing nations (Fortes et al., 2018; Alongi, 2014; Thorhaug et al., 2020a) where much of the extent of the tropical seagrass occursand where there have not been as many large-scale restoration projects. However, the exact extent of loss is poorly delineated compared to mangroves as discussed by Giri et al. (2011). In this report, we outline herein tropical and subtropical examples of successful sustainability in both Atlantic and Pacific by which we are able to provide relevant longevity models.

Hopefully, both coastal resource managers can utilize these longevity data as background substantiation for much greater restoration project funds, as well as citizens, who can engender support and confidence for restoring seagrass through awareness of global seagrass decimation. Southeast Asia is an area estimated to have been lost 30–50% of their seagrass (Fortes et al., 2018; Alongi et al., 2016). The tropics frequently have ecosystem habitats and fundamental processes very different, more fragile and stressed, than temperate or Arctic zones (Moore, 1958,Moore, 1972; Eklöf et al., 2011). Among relevant points (Moore, 1958) linking knowledge among ocean basins about the global marine and estuarine tropics are that many seagrass species have cogenitors which are closely-related physiologically, residing in the Atlantic, Pacific, and Indian Ocean tropics (Marcus and Thorhaug, 1981, and Thorhaug et al., 1986). This and knowledge of the relatively recent evolution of Pacific vs. Atlantic tropical species, lend evidence toward similarities for comparisons of co-genitors and allowed use of restoration techniques and methodologies across the two oceanic realms. This can provide information about sustainability of genera restored, and long-term results among these three regions.

It is clear when seagrass is lost, many of the seagrasses' services are lost (Norlund et al., 2018). However, data documenting restored seagrass services in tropical/subtropical areas have not been carried out consistently and over time to provide marine resource management with hard data as to services returned , except in the Atlantic USA subtropics. In the Atlantic, some detailed recolonizing studies were carried out on fisheries food webs (McLaughlin et al., 1983; Bell et al., 1993; Sheridan et al., 1998; Rezik et al., 2019), and for carbon sequestration in 8 restored seagrass beds within the Gulf of Mexico (Thorhaug et al., 2017) and globally (Arias-Ortiz et al., 2018). The key services essential to resource management appear to be the following. 1.) The resilience of the shoreline is stabilized with seagrass creating biological shoaling for shorelines and baffling of water-born particles into stabilized sediment material (Wanless, 1981, 2010; Hall et al., 2006); 2.) The service of recolonized fisheries nurseries (McLaughlin et al., 1983; Bell et al., 1993; Sheridan et al., 1998) and animal biodiversity habitat (Thorhaug and Roessler, 1977; Livingston, 1984; McLaughlin et al., 1983; Norlund et al., 2018); 3.) The sediment burial of organic carbon, one of several key solutions to Climate Change, shows carbon sequestered by seagrass is 3 times higher than tropical rain forests (Duarte et al., 2005; Fourqurean et al., 2009; Pendleton et al., 2012) and has been regionally (GoM) shown to be comparable in amount to Gulf of Mexico mangroves' sedimentary organic carbon (Thorhaug et al., 2019). In tropical nations, the seagrass carbon buried ranges globally from 2 Mg ha-1 to 750 Mg ha -1 in the first meter (Alongi et al., 2016) including carbon buried after restoration (Thorhaug et al., 2017; Greiner et al., 2013; Marbà et al., 2015). 4.) Nutrient cycling created by natural and restored seagrass (Costanza et al., 2017); 5.) Seagrass creates improvements in water clarity. Unfortunately, in many tropical newly-industrializing nations neither legislators, government resource managers, nor the general public appreciate the values of seagrass services sufficiently to halt the degradation. In Southeast Asia seagrass degradation has been estimated to be 30% or more in extent (Green and Short, 2003; Alongi, 2014; Fortes et al., 2018; PEMSEA, 2016; Thorhaug et al., 2020b).

A.)Introduction to the major example in Texas estuaries. Texas estuaries seagrass loss and restoration to mitigate loss

Texas seagrass restoration efforts have the following features: 1.) a history of over 30 projects with monitoring and observations over an entire regional set of restored seagrass project lifetimes; 2.) the prior historical anthropogenic impacts of intense Gas and Oil and other industrialization and urbanization creating seagrass decimation, which implies a large need for restoration; 3.) a clear management attitude pivot presently encouraging seagrass restoration; and 4.) lack of a previous restoration historitcal overview. According to the Texas General Land Office review by Pulich (1998), Texas has lost more than 70% of its seagrasses due to intense industrial and urban anthropogenic activities for over 150 years, leaving the bulk of the remaining 95,101 ha (up to 80% or 74,867 ha) existing in a single estuary, the Laguna Madre. Texas possesses the fourth longest USA coast line in the lower 48 States. It is a major center of USA gas and oil refineries, mostly sited in estuaries, along with needed ports and their navigational channels to export energy and other products. The Texas energy industry includes 45% of U.S.A.'s fossil fuel refining capacity plus nearly 40.5% of the USA's gas and oil drilling and extraction (far more than any other state). Houston-Galveston Bay (according to TAMU report) surroundings have more chemical facilities and refineries than any other place in the world. The GoM has an economic basis (Mexico and USA) of $124 billion per year (Yoskowitz, 2009) primarily from gas and oil, shipping, ports, fisheries, and tourism. Seagrass has diminished significantly throughout the entire western and northwestern Gulf of Mexico (GoM), including Texas , whereas Mexico and Louisiana have large gas and oil production with the remaining, totaling 121,344 ha

Table 1
The overview of Texas seagrass restoration projects, 1970's to 2010's. Extent, species, number of planted units. *H=Halodule wrightii, HP = Halophila sp., S=Syringodium fileforme, T = Thalassia testudinum, R = Ruppia speciesf.*

Investigator & cited publication	site	Seagrass species	Size planted area in meters square	Type planting unit	Number planting units
Belaire (various dates 1980–2010)	Texas sites	H, HP, S, T	1,012,777	Plug,	1,042,669
Thorhaug 2001,2014, 2016, 2017	Laguna Madre, CorpusChristi, Aransas, Mategorda Galveston Bays	*H, HP*	625,196	Plug	596,615
Sheridan (2004) Sheridan (1997)	Redfish Cove, 27°365′ (North) 97°15′ (West) Snake Is, Galveston Bay, Tx	*H*		Plug, PP mechanical	10,476
Hammerstrom et al.(1993, 2006)	Galveston, Tx	*H*		Plug, mechanical	3518 1720
Kennedy et al.	Galveston,Tx	*H*			16,000
Carangelo et al. (1979)	Corpus Christi Bay27°94′ (North) 97°02′ (West); 27°84′ (North) 97°4′	*H*	200	Sod & plugs	307 36 72
Maristany et al. (2018)	Corpus Christi Bay	*H*	94,577		108,610
Phillips (1980)	Redfish Bay, 27°849′ (North) 87°141 (West) Galveston Bay 30°009′ (North) 84°335′ (West)	*H*	20	Plugs Sprigs	200
Total			**1,732,770**		**1,872,018**

seagrass located in the Western Gulf of Mexico, compared to 850,758 ha in the Eastern GoM, where purposely there is no Gas and Oil industry. Investigators have found 2500 ha in Louisiana (Poirrier and Handley, 2007), 57 ha in Alabama (Heck et al., 2015), 250 ha in Mississippi (Moncreiff, 2007) plus Texas's 95,101 ha (Pulich, 1998). Only 25,000 ha is reported by Chmura and Short (2015) in Mexico's GoM coast indicating further significant Western GoM loss due to Mexico's petroleum industry, industrial growth, and fisheries practices. Although in Yucatan Peninsula Campeche et al. (2018) report of a large meadow. This means the GoM contains just over 1,000,000 ha or 10,000 km^2 representing 5.8% of the global total. The original Gulf of Mexico seagrass extent in Pre-Columbian era is estimated at probably several times the present amount (Duke and Kruczynski, 1992). One of the three major North American fisheries occurs in the GoM, consisting chiefly of shrimp (78%), oysters, squid, and crab plus an array of commercial and recreational fishing. Additionally tourism industry based solely on natural resources produces economic returns of $25 billion dollars to the Gulf of Mexico states and employs 8.3 million workers (National Fish and Wildlife, 2011). However, fisheries are declining both in USA and Mexico (Soto et al., 2014) partially due to their seagrass habitat decline. The biodiversity of estuarine benthic food webs is dependent on seagrass as are specific endangered species such as Whooping Cranes, Kemp Ridley turtles, plus other species like Brown Pelican for feeding habitat.

1.1. Objectives

The review's objective is to integrate and compare for the first time key large-scale tropical and subtropical seagrass restoration trials' concerning long-term seagrass longevity, across five differing areas of the tropics/subtropics in the Atlantic, Pacific and Indian Oceans (to the edge of the sub-temperate).The hypothesis is that seagrass once successfully restored continues to live at the recipient site for decades. We use as detailed examples for seagrass restorations' longevity within Texas estuaries particularly the million and a half Planting Units that were planted at 83 sites as well as 4 other regions.

2. Methods

2.1. Review process of projects

2.1.1. Atlantic Ocean: Texas projects

a. Overview of physico-chemical and geological constraints in Texas Estuaries

The Texan Gulf of Mexico coastline is 591 km with 5405.8 km of shoreline including estuarine perimeters. All Texas estuaries lie behind sandy barrier islands with variously-sized passes to the open Gulf of Mexico. Currents in GoM circulate from the Yucatan Straights clockwise to the northwest with a counter-current running close to shore near the Texas coast. Texas rivers usually circulate slowly from the estuarine river through each estuary of varying shallow depths while exiting the western side of estuaries through narrow passes . This is in contrast to the rapid rivers exiting through large delta Passes on the Atlantic seaboard of the North American coast. Texas Rivers emanate from the Rocky Mountains to more proximate origins in Texas with a total Water shed area of almost 700,000 km^2.

b) Restoration reviews

Some of the information already has been published about Texas seagrass restoration trials while other information was chiefly only in Texas government reports. A small additional amount we found through internet and investigator searches. There were a number of sites which were planted from South Laguna Madre to Galveston Bay (listed in Tables 1, 2 and 3) not in the published literature. Many sites had been anthropogenically impacted by dredge and fill, industrial and urban effluents, shoreline modifications and fill including coastal roads and causeways, ports, channels, and marinas, and other impacts such as vessel groundings.

c. Donor Beds

The plugs and sprigs for the large and medium-sized projects were generally extracted as 4.5 cm to 10 cm diameter plugs. Each plug was taken at 1 m intervals from permitted (TGLO, TDWL, USAEC) naturally-occurring seagrass beds, generally within 1.5 km proximity to restoration site. Great care was taken by Belaire and Thorhaug restoration teams to protect the donor bed from damage. Required joint monitoring of donor beds by the environmental permitting agencies occurred with regular planting investigator monitoring. Noteworthy is no report of any damage to donor beds. In instances, donor beds also consisted of sites previously restored by a seagrass planter. Plugs averaged 25.8 cm square for Belaire and Thorhaug work, thus one ten thousandth of a hectare was used to restore one half hectare. Sprigs were approximately 7–10 cm length with apical meristems. Sheridan used one unusual donor bed: the inflow wrack from the Flour Bluff Power Plant in North Laguna Madre, from which he transported material to Galveston Bay. *Fertilizers.* Fertilizer compounds were used for one-half (2.5 ha) of a 5 ha revegetation during the early stages (2 weeks old) of the Predator

Table 2
Extent, species, number of planted units, success, monitoring coverage in hectares, site from Belaire plantings in Texas 1987–2013.Species *H*=*Halodule wrightii*, *HP* = *Halophila* sp. *S*=*Syringodium fileforme*, *T* = *Thalassia testudinum*, *R* = *Ruppia species*. Projects monitored by TGLO and USAEC.

Investigator & citation date	Location receptor site (sponsor)with geo-references	Area m^2 planted. Area still Alive?	Species planted	Number planting units.	Survival % after 6 mo TGLO & USACE approved	Coverage % 18–36 mo. TGLO & USACE approved.
Belaire Consulting(1989)	Corpus Christi, Aransas Bays. CCOG. 26°10 (North) 97°17 (West)	182,110 yes	H	225,000	90	90
Belaire Consulting I, 1990a, 1990b	Copano Bay. 26°10 (North) 97°17 (South)	3055 yes	H	1750	90	74
Belaire Consulting (1987)	Redfish Bay. 26°10 (North) 97°17 (West)	12,141 yes	H	7500	70	99
Belaire Consulting I (1990a, 1990b)	*S. Laguna* Madre. (EDC) 26°10 (North) 97°17 (West)	180,087 yes	H	222,500	80	80
Belaire Consulting I (1990a, 1990b)	Central Laguna Madre. (Bright Co) 26°10 (North) 97°17 (South)	3035 Yes	H	3750	80	80
Belaire Consulting I (1990a, 1990b)	N. Laguna Madre. Pipeline, fill in channel, Spoil Isld. (CC transmission Co.) 26°10 (North) 97°17 (West)	218,533 Yes	H	270,000	74	90
Belaire Consulting I (1990a, 1990b)	Matagorda Bay. Restored pipeline trench28°68 (North) 95°94 (West)	14, 165 Yes	H	17,506	40	47
Belaire Consulting I (1992a, 1992b)	Upland scrape down. Central P&L. 26°10 (North) 97°17 (South)	4047 Yes	H	5000	44	56
Belaire Consulting (2002)	Laguna Madre. wave barrier const, (Mitchell Energy) 26°08 (North) 97°21 (West)	99,464 Yes	H	0	N.A.	62
Belaire Consulting I (1995)	N. Laguna Madre scrape down barrier Island26°08 (North) 97°21 (West)	84,966 Yes	H	100,000	50	60
Belaire Consulting I (1993)	N. Laguna Madre Refilled deep prop scar (Le Boef Bros.) °10 (North) 97°17 (West)	24,282 Yes	H	30,000	40	74
Belaire Consulting I (1995)	Corpus Christi, Laguna Madre Scrape down barrier island26°08 (North) 97°21 (West)	87,698 yes	H	106,850	67	50
Belaire (2002)	Corpus Christi, Laguna Madre Scrape down oil causeway (Oleander) 26°10 (North) 97°17 (West)	27,314 yes	H,R, HP	0	N.A.	73
Belaire Consulting I (1995)	Abandoned causeway scrape down26°10 (North) 97°17 (West)	1991 yes	H	2460	60	76
Belaire Consulting (2009)	N.LagunaMadre. Scrape down upland (S.Padre Develop Corp.) 26°10 (North) 97°17 (West)	1578 yes	H	1500	67	67
Belaire Consulting I (2010)	Redfish Bay. Scrape down City dump (Kiewit Offshore) 27°87 (North) 97°12 (South)	8499 yes	H	2573	54	56
Belaire Consulting I (2010)	N. Laguna Madre; unauthorized placement dredging. (La Quay Dredging) 28°68 (North) 95°94 (West)	13,396 yes	H, HP.	15,500	64.5	64.5
Belaire Consulting (2009)	S.Laguna Madre, Port Isabel. Scrape down dredge spoil. (Subsea 7) 27°81 (North) 97.10 (West)	7295 yes	H, S	9000	60	72
Belaire Consulting (2011)	Mesquite Bay. Wave barrier construction (Chaparral Energy), 26°10 (North) 97°17 (West)	20,910 yes	H	0	N.A.	20
Belaire Consulting (2013)	Shamrock Isd.,CorpusChristi. unvegetated bay bottom 26°10 (North) 97°17 (West)	18,211 Yes	H	21,780	N.A.	N.A.
	Southern Texas Gulf Coast	**1,012,777 m^2**		**1,042,669**	Mean = **51.5** Range 40–90	Mean = **64.5**

Island planting by Thorhaug (2001a, 2001b) as required by an USACE permit. No statistical difference occurred between "not fertilized" and "fertilized" PUs with growth or density measured by lateral growth rate, increase of density of short shoots, or increase in root/rhizome biomass. Thus, few further fertilization experiments were carried out for the subsequent Thorhaug 10.6 ha at *CCOG*, or 16 + + hectares at the Exxon Channel except experimentally at its two ends (well head and T-head). Apparently, no fertilizer was used by Hammerstrom et al. (1998a, 1998b), Maristany and Carangelo (2018), or Philips. However, fertilizers were used in specific attempts by Sheridan and several trials by Belaire.

Other detail of methodologies.. There are a series of publications and government reports from Belaire (1990–2010) and Thorhaug (2001a,

Table 3
Texas seagrass restoration projects of Thorhaug 1994 to 2017. Extent, species, sites, number of planted units, success. The species abbreviations are *H*=*Halodule wrightii, HP* = *Halophila sp. S-Syringodium fileforme, T* = *Thalassia testudinum, R* = *Ruppia species*. CC=Corpus Christi, LM = Laguna Madre All units monitored and certified by TGLO and TPWL the ones prior to 2005 also monitored USAEC.

Investigator citation date	Receptor site	Area m$^{2.\ \text{Still Alive ?}}$	Species	PU number	Success%
Thorhaug (2001a, 2001b)	Test Canal Head Laguna Madre. 27°319,357′ (North) 97°19,158′ (West)	1533 yes	*H*	1,533	65
Thorhaug (2001a, 2001b)	Test T-Head L.M. 27°313,842′ (North) 97°192,207′ (West)	135 yes	*H*	90	85
Thorhaug (2001a, 2001b)	L.M. Mid-Exxon 27°313,842′ (North) 97°192,207′ (West)	29,538 partial	*H*	29,538	65
Thorhaug (2001a, 2001b)	Well Head, Exx.,L.M. 27°310,969′ (North) 97°193,568′ (west)	40,468 Yes expanded	*H,HP,R*	40,468	70
Thorhaug (2001a, 2001b)	Canal Head, L.M. 27°310,969′ (North) 97°193,568′ (west)	40,489 yes	*H,HP*	40,468	73
Thorhaug (2001a, 2001b)	Predator Isl., L.M. 27°322,022′ (North) 97°111,341′ (West)	59,489 Yes expanded	*H,R*	59,489	93
Thorhaug (2001a, 2001b)	Laguna Madre, CCOG, 27°313,076′ (North) 97°194,392′ (West)	105,218 Yes, greatly expanded	*H,HP*	105,218	77
Thorhaug (2001a, 2001b)	Laguna Madre. N-Middle canal, 27°310,969′ (North) 97°193,568′ (west)	40,468 partially	*H,RP*	40,268	77
Thorhaug (2001a, 2001b)	Laguna Madre. Mid-Exxon 27°310,969′ (North) 97°193,568′ (west)	40,468	*H,HP*	40,468	65
Thorhaug 2013, 2016	San Luis Pass in Galveston Bay 27°313,076′ (North) 97°194,392′ (West)	120,000 Yes expanded	*H*	110,000	92
Thorhaug, 2013	Aransas/St. Charles Bays 27°310,969′ (North) 97°193,568′ (west)	40,000 Yes expanded	*H*	40,000	72
Thorhaug, 2013	Aransas/St. Charles Bay17°59′ (North) 76°48′ (West)	1 728 yes	*H*	1755	100
Thorhaug, 2013	Shamrock at Mustang Island Shoreline 25°454,232′ (North) 80°090856′ (West)	12,000 Partial	*H*	12012	79
Thorhaug, 2013	CroakerHolestream 25°481,334′ (North) 80°110,640′ (West)	53,683 Partial	*H*	40,000	63
Thorhaug, 2013	Croaker Hole flats. 30°245708'(North) 81°244,509′ (West)	20,000 Yes, expanded	*H*	555	74
Thorhaug, 2013	Croaker Hole shelf. 30°245,708′ (North) 81°244,509′ (West)	**20,000** Yes. expanded	*H,HD*	500	69
Total		**625,**238		559,757	**Mean = 76.2**

2001b), and Thorhaug and Schwarz (2013–2017) which detail methods for results in Tables 2 and 3. Sheridan outlines placing floating *Halodule* sprigs from the Flower Bluff power plant within a barrier in Galveston Bay. The Sheridan transport conditions and methods, etc. are not clear. The results of this sprig project are in Table 1. Monitoring measurements included ground truth with number of surviving Planted Units (PU), blade measurements, coalescence, and dimensions of planted areas during first 18 to 60 months After which ground truth observations and the use of Google Earth Pro and other professional aerial photography measurements in subsequent years. The subsidiary measurements of services in some sites included animal recolonization (Sheridan, 1997, 2004 and Thorhaug, 2017) and carbon sequestered in sediment at 8 sites 4 sites (Thorhaug et al., 2017).

2.1.2. *Atlantic Ocean. Biscayne Bay, Florida Projects*

a) *Overview of physico-chemical and geological constraints.* Biscayne Bay sits at the southeast tip of Florida at the edge of tropics, separated from the Atlantic by barrier islands composed of sunken coral reefs. It has a series of ocean passes through which tropical Atlantic waters from the wide Atlantic and/or the Florida Current emanating from the Gulf of Mexico enter the Bay whose dimensions are 61.2 km length and 17.7 km width. The underlying bay geology is an ancient coral reef with calcium carbonate features. Both east and west shores are also underlain by Coral as is the entire body of the terrestrial tip of Florida. The man-created drainage canals from the Everglades National Park and agricultural land pour waters via sheet flow into the western Bay for the 6 month rainy season (May to October). The primarily shallow Bay with a major US urban area at the north has either dredged or filled 50% of North Biscayne Bay bottom land (Chardon, 1976). *b.) Methods and detailed results for various sites* are previously published in Thorhaug (1974, 1979, 1981, 1985, 1987, and 2000). There were 4 major phases which occurred at differing locations, using various species and methodologies. Between 1973–74 at Turkey Point two corridors were constructed on either side of the recently closed effluent canal from one nuclear power and two fossil fuel power generating plants onto a bottom type composed of barren sand and peat sediment, leaving a center barren control strip *Thalassia testudinum* where three-week-old seedlings were anchored with electric-tie anchors in 0.6 to 1 m depths going bay ward from 6.5 m offshore. The first control areafor natural recolonization times and species was located at a second fossil power plant closed during this time frame, several km to the north. A second control was used for both barren and naturally-occurring seagrass density and faunal assemblage, 0.5kmto the south. . The third control was a barren strip left purposefully between the two planting corridors. c.) *Restorations between 1978–9 and 1981–2* test plots of 0.4 ha each were constructed at a series of sites to determine if restoration could occur in variously impacted regions of North Biscayne Bay from Mercy Hospital (Coconut Grove) to Bay Harbor Islands (Surfside). These restoration sites were also tested plugs and sprigs acrosseach of 3 species (*Thalassia testudinum, Halodule wrightii and Syringodium filiforme*) plus seedlings for *Thalassia testudinum.* Controls for these regionswere proximate natural seagrass beds and barren impacted by some disturbance. Much of the donor material was permitted (USAEC) from 36th St Causeway basin. Some from South Biscayne Bay or Florida Keys. A winter-test-planted area of 0.4 ha occurred in the Viscaya channel agreed with sponsor and permit agencies to test planting during winter conditions, a variable never before tested in the subtropics. The 36th St Causeway northwest side was planted in 1978 with *Thalassia* seedlings at 0.3–0.6 m, *Halodule* plugs in Shallow waters, *Syringodium* sprigs deeper than 0.6 m (Thorhaug, 1977). d.) *Restoration between 1982, 1984–5*, large scale plantings were made at 5 sites between Dinner Key and 36th St Causeway, chiefly utilizing *Halodule wrightii* by sprigs plus *Thalassia* by plugs (mixed with *Halodule*), and *Thalassia* sprigs, plus seedlings. Some *Syringodium* sprigs were used at 24th St. d.) In 2000, 20,000 plugs of mixed *Halodule, Syringodium, Thalassia* also utilizing 4000 *Thalassia* sprigs were planted at the 24 ha site of Port of Miami Island. Donor beds were located to the southwest shore of North Virginia Key. e.) *Use of anchors*: There were anchors used for *Thalassia* seedlings at Turkey Point and in some 1981 test plots, not for *Halodule or Thalassia* sprigs, nor for plugs or mixed plugs *(Thalassia/Halodule)*. No fertilizers were used. Energy types varied from an open Atlantic high-oceanic-fetch wave action at Mercy Hospital and Grove Isle sites, to very high currents experienced at 24th St., to medium energy environments at more sheltered sites such as Virginia Key. f.) *Light:* The light varied distinctly from extremely low to high levels. Low light levels were experienced at the very turbid sites such as north of 79th St. This site was continually stirred by winds and tides at test plots in North Biscayne Bay. High light levels were experienced in the clearer and shallow waters at Turkey Point, Grove Isle, and the Port Island. The sediment was chiefly course to medium quartz mixed with calcite sand, with little mud and some peat on southwestern banks such as Turkey Point. g.) *Planting season* of one single large test site at Viscaya Channel near Mercy Hospital was agreed with federal agencies and sponsor as a test of seasons in January, February, which failed, being attributed to cold weather. The remainder were planted from April through to September. h.) *Monitoring*: Measurements included ground truth along with federal natural resource management agencies staff inspections (USACE, NMFS, EPA) including survival, blade measurements, and lateral growth length during first 36 months, then ground observations and aerial imagery (including Google Earth Pro and other aerials).along with decadal measurements in subsequent years, including some blade measurements, health, animal recolonization at Turkey Point in year 3–4 and sediment analysis including carbon analysis in 2015. The project sponsor for plantings 1981–2 and 1984–5 authorized an environmental consulting company to count units planted in the first months post-planting. This was inadequately carried out, and frequently done immediately after severe storms by poorly trained and poorly informed personnel with inadequate supervisors, none of whom had expertise in seagrass biology. This is the sole example across the globe of a third party consulting firm monitoring a seagrass restoration project excluding the planting parties, which we can ascertain (Van Katwijk et al., 2016). There was no long-term follow up by these monitoring contractors, so preliminary blade absence (in first months) was recorded as plant death.

2.1.3. Atlantic Ocean: Jamaican projects

a.) *Overview of Physico-Chemical and Geological Constraints.* The Caribbean Island of Jamaica sits south of Cuba and Hispanola Islands in the Greater Antilles. The ocean waters are influenced by the Caribbean Sea to the south and an Atlantic Ocean influence to the north, with passages directing large currents from east and west. Jamaica's south coastline sits on the secondary flow-through pattern of east to west currents in the Caribbean, with much of the northwestward flow channeled through a trough southwest of Jamaica (Gyory et al., 2019). The geology of the island is an expression of its location. The island sits at the edge of the Caribbean Plate and is acted on by two forces. The basement of the island consists of Cretaceous island arc and back-arc basin sequences formed above a subduction zone. The covering rock is of mainly Eocene to Miocene shallow water limestones from coral reefs, uplifted due to the presence of a restraining bend along the major strike-slip faults that bound the southern edge of the Gonâve Microplate to the north of the island (Maurrasse, 1993). b.) *A set of test plots of 19 sites* each chosen for importance by the Jamaican Department of Natural Resources representing distinct anthropogenic disturbance types were tested for 3 seagrasses *Thalassia testudinum, Syringodium filiforme and Halodule wrightii.* Two methodologies (from seedlings to sprigs andplugs) were used for each species (Thorhaug et al., 1985). Test plots of 10 m by 10 m were monitored to explore where each of the seagrasses would persist given the pollution intensity at each site. Donor beds were proximate to planting areas in all cases. A larger urban polluted site at Kingston Harbor, located in its western \region on the east side of the causeway from the Harbor to Portland, was planted with aid of a mixture of Jamaican fishermen. This was to test the fishermen's ability to plant correctly under direction, by trained planters using plugs of *Halodule* mixed with *Halophila decipiens,* and some *Thalassia testudinum.* Depths of Jamaican plantings were 0.5 m to 5 m; light was medium to high, except Negril's deep station. No anchors or fertilizers were used at the sites, except in Montego Bays' open ocean tests of anchor types. Energy levels varied from high to low. The planting season was September to October fall 1984. Measurement of results were carried out along with Jamaican Government Dept. Natural Resource Management (Beverly Miller, Director), and Jamaican University of West Indies Botany department staff (George Sidrak, Chair) which included ground truth, blade measurements, and dimensions of vegetated sites during first 18 months. This was followed up within subsequent years with ground observations plus Google Earth Pro and other aerial imagery measurements. c. *Constraints of conditions on restorations.* Background pollution varied from high in Kingston Harbor, and near thermal power plants, plus Montego Bay's dredge and fill with relatively low urban pollution at Negril. Seagrass tolerance and success was tested by Thorhaug and Jamaica Department of Natural Resource Management, who chose types of key pollution. This included thermal effluents, sewage, riverine runoff with high sediment load, bauxite tailings, cement tailings, dredge and fill, oil spills, construction of reinforced shoreline on seagrass, and peat mining. Methodological details are found in detail in Thorhaug et al. (1985) and are similar to Thorhaug (1985) test plots. Generally, the planting sites were generally within Jamaican estuaries behind barrier islands with substantial rivers' watersheds draining coastal plains .

2.1.4. Indian Ocean. Western Australian Projects at subtropical at the edge of sub-temperate

The variable currents in the Eastern Indian Ocean mix along the Western Australian coast in a seasonal pattern with highly diverse ecosystems ranging from sub-tropical to temperate due to changing current patterns, and environmental conditions. Into this mixture of climates where corals and tropical mollusks and fish “rub elbows” with temperate biota, a large-scale project of 120,000 planted units over almost 3 ha occurred on the estuarine side of barrier islands in the Indian Ocean (Table 4, Fig. 6). *a.)* Methodologies*.* After detailed experimental testing of various factors, the final methodology (sprigs showed higher survival than plugs), depth (medium depth had highest survival), anchoring systems (sprigs tied to frames with large metal staples), and species, large-scale project methods were determined to be best practice in this region. The final methods restored chiefly *Posidonia australis,* with trials *of Amphibolis griffithii* previously utilized in smaller projects. Planting units of 120,000 sprigs were attached to non-toxic frames which were stabilized by anchors into the sediment by scuba

Table 4
Overview of major regions with examples of Tropical/ Subtropical large-scale plantings with follow-up observations from 1973 to present in Pacific, Indian, and Atlantic Oceans (including Gulf of Mexico) by a series of investigators (Verduin et al., 2012, 2019, Paling et al., 2001a, 2001b, Paling and Van Kuelen, Horn et al. (2009), Verduin and Van Kuelen, 2010; Kiswara, 2013, Kiswara, 2018; Belaire publications from 1990a,b to 2011); Thorhaug, 1974,1978,1981,1983,1985,1987,2001, 2017; Thorhaug et al., 1985).

Restoration citations	Location. final extent (when possible).	Year planted and # years	Seagrass species planted	Number of planting units	Longevity, comments
Biscayne Bay to Card Sound, Florida. Thorhaug, 1974, Thorhaug and Hixon, 1979, Thorhaug, 1983 Thorhaug, 1985, 1987, 1991, 2000,	Biscayne Bay, Miami, Fl. TP = 0.4–1 ha 24th = 9.09 ha GI = 32.2 ha MO = 84.98 ha Test plots = 5.25 ha	1973, 1978 1981–2, 1983, 1984 2000	*Thalassia testudinum, Halodule wrightii, Syringodium filiforme*	TP = 83,000 24th = 90,900 GI = 322,000 MO = 849,800 Tests = 52,500 Many expanded	For bulk of PU: 35–47 years, as long as plantings existed. Persistent restorations expanded .
Jamaica. Thorhaug et al., 1985	Jamaica, Kingston 20 locations, Harbor, Montego Bay, Ocho Rios, 7.8 ha	1982–3	*Thalassia testudinum, Halodule wrightii, Syringodium filiforme* Plugs, sprigs, seedlings	Test plots = 54,000 expanded Ft. Aug. = 54,000 expanded	43 years as long as plantings existed in a series of impacted sites with several exceptions.
Australia.Verduin & Van Kuelen 2012	Western Australia, Cockburn Sound 2.6 ha	2009–2012	*Posidonia Australis, Amphibolis griffithsii*	123,185	6–10 years as long as plantings existed. Initial survival 68%
Australia. Paling et al.2001b	Western Australia: Success Bay 0.32 ha	1998–2007	*Amphibolis griffithii, P. coriacea* *Sods*	3184	8–10 yr as long as plantings existed. Initial survival 70.0%.
Indonesia. Kiswara, 2013, 2018	Various sites in Java, Indonesia: Pari Island, Jakarta Bay *Enhalus* = 0.0025 ha, S 05 515,360; E 106 363,139, *Thalassia* = 0.0100 ha S 05 403,131; E 106 372,745	1998, 2009, 2009–2018	*Enhalus acoroides, Thalassia hemiprichii* sprigs, seedlings	1400	10 years as long as plantings existed. Initial survival 69.4%, 97.9%.
Texas Belaire in this report Table 2, Thorhaug et al. in this report Table 3. Test plots 1993–6	101.2 ha 62.5 ha	1980-present	*Halodule wrightii, Halophila engelmanii, Thalassia testudinum, Ruppia maritima*	CB = 1,042,669 expanded AT, AT + AS = 596,615 50–90% Expanded	6–33 years as long as plantings existed with Exception of Packery Channel disruption by turbidity. Also expansion.
Totals	**306.3 ha**			3,042,353 **PU**	**6 to 47 years as long as plantings existed.**

divers at 2.5–3 m depth intervals during the Australian spring. The detailed methods and early test plots can be found in Verduin et al. (2012), Verduin et al. (2009), Paling et al. (2001a, 2001b, 2003), Paling et al. (2007, 2009), Van Kuelen et al. (2002, 2003). The final plantings had high success rates. *b). Constraints of conditions on restorations.* The region was had highly energetic water movement including Indian Ocean currents, wave action, and seasonal winds. The large coastal plains to the east, contributed urban and agricultural run-off, as did the urban center Perth. However, this region was generally a less densely populated area of Australia than its eastern seaboard.

2.1.5. Pacific Ocean: Indonesian Projects

a.) Methodology. Methods are published in Kiswara (2013) and Kiswara (2018). Chiefly sprigs were used in the bulk of planting activities, with single shoots of *Enhalus acoroides* or sprigs of *Thalassia hemprichii*. Multiple sites were explored on Java (in Jakarta Bay, Pari Island, Bidadari Island also included Gedang Island, and Kuala Pasar Banten Bay) (Fig. 5, Table S-5). There were also multiple species explored in various trials (chiefly *Enhalus acoroides* and *Thalassia hemprichii,* but also *Cymodocea serrulata, C. rotundata, Syringodium isoletiforme, Halodule uninervis, H. pinifolia, Halophila ovalis, Thalassodendron ciliatum*)See supplementary material Table S-5 to find biomass of species per 5 major restoration sites). Planting depths were 0.4–2.0 m. Light intensity was high; energy level was medium. The planting proceeded without fertilizers, and mostly without anchors, although bamboo quadrat anchors were utilized in some trials. No predation was experienced at young restoration stages, thus predator cages were not needed. Although there were not a high number of PU's planted, survival was high up to 97% for *Enhalus acoroides* plantings, which sustained from when they were planted to live for a decade. *b). Constraints of conditions on restorations.* The flow-through Pacific Equatorial current (Wyrtki, 1987) are generally strong past the Indonesia islands of Java . Generally, the plantings were within estuaries experiencing strong tidal currents. Java, Indonesia is densely populated, so that sites closer to Jakarta were influenced by urban run-off and dredged shorelines. The area is prone to volcanic and typhoon natural disruptions.

3. Results and discussion of results

A.) **General results. Atlantic, Pacific, Indian Ocean Basins**

The sustainability and longevity of restored tropical to subtropical seagrass in almost all cases appears to continue once the plantings are successfully stabilized which occurred within 12 to 18 months. Conversely, it appears that those planted units (PU) not tolerating ambient conditions succumbed by 18 months at a series of sites. The exceptions were discrete major anthropogenic impacts which occurred substantially later around the areas of the planted seagrass meadows. From this initial survival time for restored seagrass, the substantial portion of the restored seagrass meadows in all three ocean basins lived for as long as the results were monitored and/or observed by their investigators, , although much longer data observations in the Atlantic restoration sites are available due to plantings decades earlier. This longevity pattern was reviewed from data extracted from 5 global tropical/subtropical regions. Of which one was Texas, spanning subtropical to tropics, three in tropics, one at the confluence of sub-tropics to sub-temperate) composed of 83 sub-sites with 304.17 ha of restored seagrass created from 3,042,353 Planting Units (PU).

The data shows that the major species restored in these trials included *Thalassia testudinum, Halodule wrightii, Syringodium filiforme, Halophila englemanii, Ruppia martima, (*above for Atlantic region*) and* for Indo-Pacific region *Enhalus acoroides, Thalassia hemprichii, Enhalus acoroides, Halodule uninervis, H.pinifolia, Cymodocea serrulata, C. rotundata, Thalassadendron ciliatum, Halophila decipiens, Posidonia Australis, P. coriacea, Amphibolis griffithsii, A. Antarctica*. In contrast to mangroves, the tropics/subtropics restored seagrass studies, investigators' trials reviewed herein did not find such an age limit. Conversely, of the planted large-scale tropical/subtropical seagrass trials presented, most large-scale attempts are presently living with the above anthropogenic disturbance exception to sustainability. Naturally-occurring blow-outs include three intense storms impacting immature seagrass restorations within weeks after planting but monitored 9 months later where these were observed to regrow from remaining lateral seagrass material after the impacted sediment areas filled with transported sand (i.e., two in Central Biscayne Bay Florida and one in Laguna Madre Texas). This pattern is unlike the life-cycle of the other blue carbon tropical habitat mangrove trees, having definite age limits wherein the trees senesce.

The exceptions from sustainability due to anthropogenic activity were the following: 1.) aAn anthropogenically-created opening of an Texas oceanic pass which created substantial water column turbidity in the North Laguna Madre. Due to creation of a ocean pass, diminished light penetration occurred (at depths of 0.3–0.4 m and greater) years after long-term seagrass survival had been established, reducing about 30% of planted seagrass in EXXON Channel in one of the five FINA and colleagues .plantings (i.e., the planting down the center of the Exxon channel); 2.) In Galveston Bay, several small restorations failed [discussed in Sheridan, 1997 and Hammerstrom et al., 2004]; 3.) In Jamaica, the following lack of success occurred: a.) a failure from areas where large oceanic-vessel create large wakes, b.) in very high-energy open-ocean reguons where wave action movesbottom sediment drastically with each intense storm, c.) very high salinities in salt ponds reaching salinities over 60 ppt, d.) fine cement tailings that result in a highly turbid water body; 4.) In Biscayne Bay, a.) in a mature restored site with smothering coming from an inadequately-supervised dredging project which injected fill into a constructed pit in the Bay very proximate to the restoration site.

The resilience to natural events appears to stimulate a potential for regrowth after the event in several cases. In three cases, severe storms physically removed newly planted units: 1.) In Texas, 2–3 ha of sediment was carried away by Hurricane Bret along with newly planted (30–45 d post-planting) seagrass plugs (Thorhaug, 2001a, 2001b). However, sediment filled into these depressions over time onto which *Halodule* regrew laterally from the side plantings within 18 months; 2.) A tornado in March 1999 in Laguna Madre Texas took approximately 20% of newly planted seagrass in an acre in a series of small round (diameter = 1 m) touch-down points. The sediment refilled the holes over 3 months and seagrass grew laterally to fill the area (Thorhaug, 2001a, 2001b); 3) In Biscayne Bay, Florida, a number of planting units were physically blown away during a gale force winter wind event in a very high energy fetch site where Atlantic ocean storms rolling through a large ocean pass proceeded to the bay west side of the bay creating large fetch within weeks of seagrass planting (Thorhaug, 1985). Additionally, in very cold weather in January, a 0.4 ha planting died , as an experiment to test the efficiacy of for winter subtropical planting. From example sets of restored seagrasses that have been impacted in some manner, we infer that the restored beds are not more resilient to severe anthropogenic activities that result in extreme turbidity or smothering by dredge and fill, than are naturally-occurring seagrass beds.

Importantly, no example of death by long-term senescence of plants was reported at any site other than the cases of clear anthropogenic impact, but rather the restored sites continued to sustain their blades' densities and root/rhizome structures.

B. Atlantic tropical/subtropical seagrass restoration examples: results of Texas seagrass restoration.

Seagrass restoration in Texas implemented during the past 25 years is outlined in the Tables 1, 2 and 3. The trials show 1,042,669 planted units (PU) for Belaire plus 596615 PU for Thorhaug (2001a, 2001b) and Thorhaug and Schwarz, 2013, 2017. These plantings demonstrate various initial planted-unit survival rates from above 90% to near 50%, a dependence on environmental site constraints. In all cases, large scale restored seagrass was documented growing laterally, creating large meadows. Each of the Belaire/Thorhaug/Schwarz site plantings and results have been objectively examined jointly with State, and atsome selected sites federal-inspectors have added to monitoring. Together Belaire and Thorhaug/Schwarz have planted close to 1 km^2,which expanded into approximately 1.4 km^2 from the commencement of these efforts. These restorations were government certified, all examined by State and most by several Federal agencies granting mitigation permits. Furthermore individual restorations (especially Thorhaug/Belaire) survived the first year approximately with 65–95% of the original planted units remaining. Note that the Texas mean survival of Planted units by Thorhaug = 75.8%, and Belaire = 64.5%, as inspected and certified by government scientists monitoring the restorations. Monitoring was done after 60 d and then monitored again after 1 y, wherein the resource agency criteria was 50% sustainable.

Throughout these decades, the restorations tolerated repeated naturally-occurring intense events including tornadoes and hurricanes. Physiological results show species tolerances to anthropological variables to differ (Thorhaug and Marcus, 1981a; Thorhaug and Booker, 1986, Thorhaug et al., 1991). For example, natural populations of *Halodule* tolerated an existing series of pollutants and extremes of natural environmental variables more successfully than the *Syringodium* populations found in more tropical estuaries such as Laguna Madre. Several *Halophila* species tolerated large salinity variations and also tolerated large light intensity variations and were found on upper sides of anthropogenically-deepened channels (Thorhaug, 2001a, 2001b). The majority of Texas restored sites persisted over time including some with expansion into adjacent bare bottoms as discussed in the individual publications cited for various locations (Table 1).

The largest percentage of the Texas restoration work was done by Belaire and Thorhaug and Schwarz (Tables 1, 2 and 3), and secondly by Carangelo and Maristany et al. (2018) (Table 1). Historically, the first Texas seagrass restorations were carried out by Carangelo with Oppenheimer in the Corpus Christi and Laguna Madre areas using 415 sods and plugs planted chiefly of *Halodule wrightii* (Table 1). A history of Texas restoration is given in Table 1. Seagrass mitigation throughout the USA became a commonplace governmental requirement for infrastructure and private sector commerce estuarine activities including industrial spills and vessel accidents for “takings” as carried out by Belaire (1990 to 2010 in Table 2) and Thorhaug's Laguna Madre large scale project commencing testing in 1993 (Thorhaug, 2001a, 2001b) (Table 3**)**. Thorhaug's first group of test plots occurred in the early parts of the planning process of Fina Gas and Oil Laguna Madre project (Table 1). Thorhaug‘s test sites in various areas, defined clearly which species and techniques would sustain most cost-effectively with various anthropogenic and environmental constraints. Belaire planted chiefly *Halodule wrightii*, but also *Ruppia maritima* and small amounts of *Syringodium filiforme* and *Thalassia testudinum (*Table 2*)*. Monitoring and/or observations were carried out more than 15 years in Belaire and in Thorhaug (Tables 2 and 3) including coalescence, abundance, health and recent Thorhaug results include key animal recolonization

(Thorhaug and Schwarz, 2017), as well as for carbon (Thorhaug et al., 2017). A recent planting (10.24 ha) by Maristany, & Carangelo occurred in Corpus Christi Bay for the Port of Corpus Christi dredging project (Maristany et al., 2018)(Table 1). Existing major Texas pollutants in the restored areas included the following: dredge and fill, bottom sediment modifications, urban street runoff, sewage, heated effluents, nutrient enrichments plus chemical additions, salinity and depth alterations, water flow alterations through channelization and land fill, soil erosion, rock mining and agricultural inputs through riverine effects.

1. ***Site locations.*** The Texas sites ranged from South Laguna Madre to Galveston Bay carried out by multiple investigators (Table 1, Fig. 2). Many of Bellaire's sites were between South Laguna Madre and the south end of the central Texas estuaries in Redfish Bay. Thorhaug's (2001a, 2001b) large scales sites were in North Laguna Madre. Thorhaug & Schwarz's sites ranged (2017) from North Laguna Madre to Galveston Bay at the northern extreme of Texas estuaries. These Belaire and Thorhaug planting sites were regulated and agreed to by State and Federal agencies (unless federally declared *de minimus*). Their geo-references, citations, descriptions of sediment, planting date, and original disturbances are found in Tables 1, 2 and 3 and Figs. 2, 7–11 and Supplementary Fig. 1–8. At some sites, substantial planning and preliminary trials went into mutual federal/state/sponsor decisions on site selection (e.g. Fina Gas & Oil of Texas scrape downs, fill of major barge scar plus auxiliary sites, Thorhaug, 2001a, 2001b). Hammerstrom and Sheridan's sites were in Galveston Bay.

2. Quantity and species of planting units. (See Tables 1 to 4**.**) The number of planting units (planted most frequently at one meter square intervals which from Port of Miami onward was required by federal permits and Texas GLO) were as follows: The Belaire projects (1990 to 2010) in Table 2 shows 1,042,669 units planted into barren sandy areas of approximately 1,012,777 m^2 *(Halodule wrightii* dominantly planted with some *Halophila engelmanii* as understory, very small amounts of *Thalassia testudinum* and *Syringodium filiforme),* and occasional *Ruppia* sp. from South Laguna Madre northward to the central Matagorda Bay (Table 2, Fig. 2). These Belaire sites included predominately barren bottom planting, but a few scrape-downs (of dredge islands and causeways) were included. The first year Belaire survival rate of planted units was overall 64.5% (Table 2), rapidly fully coalescing into *Halodule* beds, on occasion mixed with other species. These plantings persisted as seagrass beds from the time of planting until present with monitoring and observations via field and aerial imagery. In 1999 at a series of depths (0.3 to 2+ m) in Central North Laguna Madre, Thorhaug planted 596,615 planting units plugs of *Halodule wrightii* with some plugs mixed with *Halophila* sp. at 1 m intervals (into five locations of total 357,785 m2). (These occasionally included a small fraction of *Ruppia* sp. mixed into plugs.) The Thorhaug plantings resulted in a 71.7% survival mean of planted units for the first 6 months which grew into *Halodule* beds sustaining until the present (except for changes due to Packery Channel described by Williams et al. (2007) more than a half decade post-planting, causing disturbances resulting in severe water turbidity below JFK causeway. This occurred along with the removal of piping below the Exxon Chanel fill creating additional turbidity. Key factors appeared energy regime and light. This was added to Hurricane Brett's effects on 2–3 ha in CCOG portion, which 2–3 ha regrew in 1–2 yr)**.** In Table 3, this 1999 Laguna Madre FINA Gas & Oil planting included the following: 1.) A partial scrape down of dredge island restored 5.94 ha (Fig. 5); 2.) A major vessel scar from the Corpus Christi Oil & Gas Company restored 10.6 ha (scar created in the 1960–70's) (Fig. S-3); 3.) The Exxon Channel was filled with dredge material from the scrape-down island, then planting including the impacted banks of the canal about 1.6 km; 4.) Two barren bottoms sites, one impacted in 1992, the other impacted decades earlier by oil rigs placement. Thorhaug et al. (2020a, 2020b) planted 33.30 ha in depths from 0.3 to 2 m in 17 weeks. In 2013, Thorhaug placed 15,000 PU (plugs) of *Halodule* into large one to one-fourth hectare test plots ranging in location from Galveston Bay (120,000 m2 to South Corpus Christi Bay at various and larger spacing intervals). The major 2013 plantings included a multi-hectare Galveston Bay area, a second multi-hectare in Aransas/St. Charles Bay, and in 4 sites in Corpus Christi Bay, all of which have differentially expanded (Thorhaug, 2017) (Table 3). Thorhaug' (2001a, 2001b) plantings and 2013–2017 and previous test plots resulted in some large seagrass meadows in a series of distinct areas of Texas Bays, testing a series of ambient factors: water depth, sediment type, energy regime, light penetration vs. turbidity levels, salinity regimes, tolerance of seagrass to ongoing background contamination levels of various estuaries. The restored areas sustained through hurricanes and droughts, as did many of the original test plots and most of the Laguna Madre planting (Table 3) except the anthropogenic opening of Packery Channel in 2005. ***3. Test plots sites and methodologies in Laguna Madre and Corpus Christi.*** Previous to the large scale planting and as preparation for it, Thorhaug planted trial test plots (1993 to 1996) in North Laguna Madre & Corpus Christi Bay which had numbered approximately 25,000 PU, which frequently grew laterally into far larger areas over time. Testing 4 various methodologies for restoring *Halodule wright* and *Halophila sp.* (including sprigs, sods, plugs with sediment, plugs with no sediment), the following results were derived. Plugs with sediment appeared to have the highest test-plot success rate for Thorhaug (2001a, 2001b). This was used for the large-scale restoration of 5 areas at various depths in the Laguna Madre and subsequent tests in more northern estuaries. The types of original test-plot sites included extensive barren bottoms, scrape down or dredge island modification, large vessel scars not healed over decades, and areas of prior channelization which accrued sediment. About 40 ha were derived from the final test plots which resulted after ensuing years of lateral growth. [Footnote: For tests preliminary to the success of the 1999 Fina and colleagues plantings the following areas were tested: the shelf behind dredge islands just southeast of JFK bridge, the channel sides running south at the east edge and parallel to this shelf, several flats on Flour Bluff side northwest of JFK causeway, and flats north of the channel between Mustang and Padre Island of Laguna Madre, barren flats near the Power Plant at Flower Bluff, a barren channel in the present Mustang Island State Park (Corpus Christi Bay), barren areas of dredged finger canals (abandoned development on north Padre island), and in barren areas between the Intracoastal waterway and the Padre Island National Seashore.] ***4. Large-Scale Texas Results Methodologies Used.*** Thorhaug and Belaire seagrass restoration trials included five seagrass species at a series of recipient sites**.** Belaire used bare-rooted plugs in most areas about 0. 914 to 0.01 cm^2. In many locations bare roots showed success, ranging from 40 to 90%. Thorhaug (2001a, 2001b) and Thorhaug and Schwarz (2017) chiefly utilized *Halodule* plugs with sediment (plugs containing some *Halophila engelmannii* understory in several sites) about 0.00175 m^2. Choice by USA Army Corps, State of Texas, FINA, and project personnel was made in conferences from the results of test plantings 1993–95 with multiple methods (including sprigs and other species). Maristany and Carangelo (2018) experimented with sods and sprigs and experienced lateral growth in 10.24 ha. Sheridan (1997, 2004) used sprigs cast into a general area plus hand-planted sprigs. Seeds were not utilized in Texas for restoration of any species at any time as far as we can ascertain, but were used in laboratory studies by McMillan (1976, 1981) for *Halodule.* (Few seeding *Thalassia* populations have been reported in Texas and none used for restoration.) ***5. Donor beds effects for restoration material*** were monitored by each planting team and inspected by state (frequently federal) resource agencies with no reports of damage. This included donor beds in large-scale donor extraction of materials for the Laguna Madre Fina project of 1999 (Thorhaug, 2001a, 2001b). Care was taken to space donor intervals at 1 m. About 50 m square donor material total from 40 ha were taken to restore 10,000 m square restored bed (1 ha) or about 0.5% of the 40 ha. ***6. Season of planting*** was chiefly spring and through mid-fall. Success is seen in Tables 1, 2, 3. The danger of peak hurricane season was apparent to planting investigators. An interaction between storm intensity (peaking in mid-August to mid-September) with newly planted units has been explored (Thorhaug and Wanless, 2001; Thorhaug, 2001a, 2001b; Thorhaug et al., 2017). **7. *Monitoring methods: Blade Density increase over time and planting unit success.*** Blade density measured in Laguna Madre large-scale planting increased from time zero to 1–2 year monitoring period (time usually government required) as follows: time zero the blade density increased from 10 short shoots m^{-2} vs. to 1–2 yr results of 1340 to 4000 m^{-2}, dependent on site location, including energy regime, depth, light intensity, sediment type, as well as impacts, (Thorhaug, 2001a, 2001b). This blade density also varied among the naturally-occurring Texas estuaries. A large number of revegetated sites were high PU survival this, [e.g. Galveston Bay (San Luis Pass) (Thorhaug et al., 2015) and Predator (Thorhaug, 2001a, 2001b)] where they were above 90%, although the mean mitigation success overall for planting units surviving was near 60% (Tables 1 and 2) (with 50% survival State TGLO requirement. Research test plantings, ranged from 0 to 100% in plantings of Carangelo and colleagues, Phillips, Sheridan, and Hammerstrom. The time of coalescence of the average planting unit in a one unit per meter square was a median of 4–12 months, dependent on naturally-occurring site factors such as light, depth, energy regime, turbidity. Other Thorhaug and Belaire measurements included ground truth with blade measurements, and diameters of lateral growth during first 60 months. In subsequent years, then observations by ground-truth, Google Earth Pro and commissioned aerial imagery observations occurred. **8. *Other factors of importance (light, turbidity, salinity) to sustainability:*** Water column depths of restorations ranged from 0.1 to 2 m. Light was not frequently measured and reported in many studies and varied greatly daily to monthly due to wind re-suspension of barren sediment, riverine inflow with substantial turbidity from upland soil through long rivers, mining runoff from inland and stock-piled mine tailings, dredge and fill piled onto dredge islands and marshes, runoff from dredge material for real estate and navigational and marinas, organic dissolved substances from urban domestic and street wastes, and other factors including upland agricultural fertilizer stimulation of phytoplankton which dimmed benthic light for seagrasses. Thus, no conclusions on precise required light can presently be drawn as occurred in light studies on natural seagrass in the southern Texas Bays (Dunton, 1994; Onuf, 1994). The seagrasses appear to have far less tolerance to turbidity (therefore diminishing their required light) created by dredging and filling, riverine outflows of both particulate and dissolved substances creating turbidity from soil erosion (Dunton, 1994, Thorhaug and Poulos, 2016), and nitrates and phosphates from agricultural over-fertilization creating estuarine brown tide blooms cutting light (Onuf, 1994). Gulf of Mexico water inflow at the deeper stations of the 1999 planted one-mile Exxon channel occurred chiefly through the navigational channels in the eastern Laguna Madre when the largest seagrass restoration occurred (Thorhaug, 2001a, 2001b). The Packery Channel (North Padre to *S. mustang* Island) was opened in July 2005 (Williams et al., 2007). There appears to be a tolerance to the levels of pollutants currently sustained in the Texas estuaries by the dominant naturally-occurring Texas seagrasses from Laguna Madre and Corpus Christi Bay (*Halodule wrightii, and Halophila engelmanii)* northward to southern Galveston Bay. Anthropogenic impacts affecting water quality include levels of sewage (Satschi et al., 2001), petroleum products as well as other refinery effluents (Benoit et al., 1994), levels of herbicides and pesticides seen in the results in Tables 1 and 2. The seagrass plantings were resilient enough to sustain meadows over decades in these impacted bays. **9.*) High Energy Wind Events Impacting Restoration.*** There have been regular high wind events at the restored sites such as hurricanes and tornadoes. (70 hurricanes, cyclones and other extreme wind events recorded from 1980 to present on Texas coastlines from NOAA website hurricane history). For example, Hurricane Bret occurred on August 20 to 21, 1999 (category 4 at 145 mph lowering to category 3 as it passed over Padre Island in the Laguna Madre north central section). Hurricane Bret swept away a 2 ha area of 6-week-old restored plugs along with the underlying 1998 fill in a larger area of 13 ha planted seagrass units. An adjacent naturally-occurring seagrass bed to the west, in less than 0.6 m water was also highly decimated. Subsequently, into this hole occurring over two years was the normal sand accretion process typifying the estuarine processes in this portion of the Laguna Madre. Into this 2 ha-hurricane-impacted site with newly-accreted sand the densely growing restored seagrasses regrew from all sides. The deeper restored areas from this same vessel scar were not affected in the same way when Hurricane Bret passed over them (possibly partially due to lesser wind force at depths and compaction of the sediment over time after the original scarring decades prior). On the other hand, in Hurricane Harvey (2017) seagrasses showed resilience along shorelines in Galveston Bay plus in Aransas/St. Charles Bay and in parts of Corpus Christi Bay. The marshes on these same shorelines were decimated, while the seagrass at 0.3 m and more remained intact. The plantings in the tidal channel between one side of barrier islands and Corpus Christi Bay did not survive as well along shorelines post-Harvey. One documented tornado at Predator Island in March 1999 where holes of 1 m circumference were measured as blown away under newly planted seagrass units. Recovery of sediment and seagrass by lateral growth was 6 months (Thorhaug and Wanless, 2001). **10.) *Sustainability and Longevity within Texas Seagrass Restored Meadows.*** In the Texas examples, most of the long-term footprints from restored beds can be observed throughout the year due to the perennial and dioceous nature of *Halodule wrightii* and *Halophila engelmannii* (the dominant seagrasses restored). Many of the restored sites had fixed natural boundaries which included shorelines, channelization edges, other seagrass beds, or dredged areas. Texas estuaries have been transformed into underwater checkerboards by channels, structures such as causeways, land fill, artificial filled islands, navigational channels, and other anthropogenic nearshore activities. In many cases after impact which denuded seagrass from the areas, natural lateral recolonization growth (normal mode of expansion) was not possible due to adjacent barriers (e.g. navigational channels). During growth phase, the restored areas' expanding footprint clearly was demonstrated in aerial imagery matched with ground truth. However, during our restorations of planting units, we inserted planting units into large barren bottom sites allowing substantial, lateral growth occurring within these site boundaries. **11.*) Reassembly of services of restored seagrasses: animal observations, biodiversity Increase:*** This observation of restored seagrass biodiversity was captured chiefly in reports by McLaughlin et al., 1983 for Florida's oldest site (Turkey Point), and in Texas by Sheridan (1997). Biodiversity was measured in naturally-occurring Texas seagrass by Stunz et al. (2002), Levin and Stunz (2005). Thorhaug in the 2013, 2017 reports for Texas large test sites describes: Birds—Whooping Crane (at St Charles Bay/Aransas Bay only), Great Blue Herons, Tricolor Herons, White and Brown Pelicans, terns, plovers, Roseate spoonbills, Herons, Ibises, skimmers, seagulls, and other marine shore birds; invertebrates– various species of shrimp and crabs, conch, marine snails, micro-mollusks, clams, oysters, polychete worms, foraminifera on seagrass blades, and a variety of bivalves in adjacent sand. The recolonizing fish included pin fish, snapper, grouper, red fish, flounder, sea bass, and others. Note that burrowing fauna did not appear to cause restoration failure, nor was there restored seagrass fish predation of significance. Also note that epiphytes chiefly included microalgae of Chlorophytae, Rhodophytae, and Phaeophytae. There were attached macroalgal epiphytes in early stages of growth also. Rooted in the sediment Chlorophytae (Siphonales) were observed in the restored areas in the Laguna Madre. (See Supplementary Table S-1 for sequestered carbon in 4 various Texas sites in including natural seagrass, restored seagrass, always barren sediment, and impacted barren sediment.) This restored seagrass carbon was higher than natural seagrass organic sediment carbon and varied among estuaries as did the barren background controls.

C. **Atlantic tropical/subtropical seagrass restoration examples: south Florida-Biscayne Baay & Card Sound results** (Table 4, Fig. 3).

In total 1,504,000 planting units were placed into 153.9 ha in Biscayne Bay, Card Sound, Barnes Sound and Lake Surprise. Results were generally successful for the majority of sites with several exceptions. Some lived for 47 years, while others for 35 and 20 years, dependent on planting date; all lived since time of planting with exceptions detailed below due to massive anthropogenic events or high intensity natural wind events at early planting stages. ***1.) Turkey Point.*** The *Thalassia* restoration of 83,000 anchored seedlings planted by hand at Turkey Point in August 1973 (Thorhaug, 1974) has sustained 47 years (Table S-1) with over 2000 blades m^{-2} density and 116 Mg ha^{-1} organic carbon sequestered in the sediment (Thorhaug et al., 2017) plus a full array of food-web animal species (McLaughlin et al., 1983) compared to long-term animals in naturally-occurring, non-impacted seagrass (Thorhaug and Roessler, 1977). Controls for the Turkey Point seagrass restoration included a second fossil fuel power plant 15 miles north on the same bay, which closed several years after Turkey Point effluent canal closing occurred. This 56 ha control area required 20 years to fill naturally (Smith and Teas, 1977) as *Thalassia testudinum* meadow grew in from the adjacent bay by lateral rhizomal growth (Tomlinson, 1974). Second and third controls were barren areas between planted corridors, and natural vegetation 1 km south which had not received the effluent effects. The Turkey Point general physico-chemical and ecosystem data have been published in Bader et al. (1970a, 1970b) (Bader et al., 1971, 1972, 1973, 1974; Thorhaug et al., 1973) as well as an overview of general aspects of Biscayne Bay (Thorhaug and Volker, 1975). Two nuclear power plants plus 2 fossil power plants and control sites were described in the overall data. Published initial restoration description (Thorhaug, 1974) along with chemical, physical oceanography, faunal and fisheries and seagrass dynamics aspects of the Turkey Point (Thorhaug and Roessler, 1977) occurred for both the effluents of the nuclear power plant and larger test areas. Measurements included ground truth with blade measurements and lateral growth diameters during the first 48 months, then supplemented by ground-truth observations plus aerial imagery and Google Earth Pro observations in subsequent years. In some subsequent years, blade counts and sediment samples were obtained. The faunal food web was also well documented (Thorhaug and Roessler, 1977, in Bader 1969, and then Bader and Roessler reports below 1970–1975) for controls of effluent and post-effluent faunal changes. The post-seagrass-restoration recolonized animal study carefully carried out by Smithsonian invertebrate experts (McLaughlin et al., 1983) indicates the entire food web returns 3 years after *Thalassia* seedling restoration in this *Thalassia*-dominated seagrass habitat. These investigators found a particularly large increase in shrimp, as well as fish, macro- and micro-invertebrates in this carefully executed study. ***2.) North & Central Biscayne Bay.*** The second series of plantings in north and north central Biscayne Bay are published in Thorhaug (1978, 1981, 1985, 1987, 2002). First, an array of restoration test plots were planted (Thorhaug and Hixon, 1975) in the Central and North Biscayne Bay, Florida, then large-scale restorations occurred of 136.3 ha with more than 1.3 million planted units, which have sustained substantially for 35–37 years (exceptions noted below of one planting partially blown out at Mercy Hospital Project I). Four of these project sites are herein described as examples: ***a.) 24th ST*** (9.09 ha) planting in 1983 (200,554 *Halodule/Syringodium* plugs, 73,440 *Thalassia* sprigs persisted throughout the planted area and extending beyond the perimeters (Supplementary Fig.S-4). (After planting in 1983, *Thalassia* sprigs were surviving at 89% survival at medium depth and 88% greater depth; *Halodule/Syringodium* were surviving at 35% shallow and 38% medium depth in first year, this expanded and blades grew exceptionally long; although there were multiple disturbances several decades after planting (re-dredging Intracoastal waterway, 2015–8 Port of Miami Channel deep dredging and poorly-executed fill with much material loose dumping into whole in bay above 36th St.). The prior pre-planting history of this site included a major sewage outlet; however, the healthy restoration site still survives. ***b.) Grove Is*****le** 32.2 ha with over 274,434 mixed plugs of *Thalassia/Halodule* PU into 73 planting sub-sites within the site persisted since 1984 planting (Supplementary Fig. S-5) while post-planting included major hurricanes (Andrew, etc.), and many other intense storms. ***c.) The Port of Miami SE Island "oil spill"*** planting in 2000 of 12,000 *Halodule wrightii* with mixed *Thalassia* plugs, 3000 *Thalassia* sprigs restoration planted into area 12,212 m^2 consisting of large patches of barren sand areas with deep propeller scars and multiple contaminants. This expanded into about 4.4 ha, including expansion of the deeper *Thalassia* plantings along the south edge of the this Island along Fishermans' channel with 87% survival (for the State of Florida Emergency Management Department which Oil spill island planting has shown continued persistence from 2001). ***d.) The "outer area" of Mercy Hospital*** (bayward side) Phase III Mercy Hospital seagrass planting with 84.98 ha and 849,800 PU which has grown *Halodule* in the normal patchy pattern seen in previously impacted "mid-bay seagrass" found from Central Biscayne Bay to the south with groupings of *Thalassia*-dominated vs. *Halodule*-dominated large seagrass stands. In these meadows, large patches have been variable among years dependent on hurricanes and winter storms (due to large Atlantic oceanic fetch coming through the wide 16.2 km gap between 2 barrier islands (Key Biscayne and Sands Key) fringing the Atlantic side of the Bay, known as "the Safety Valve". [Footnote: Two of the Biscayne Bay plantings are not herein used as examples of longevity but will be discussed elsewhere: e.) Viscaya channel done for the first time globally (by demand by Port officials) as a test of potential winter subtropical planting and f.) ***The first (1983) Mercy Hospital planting.*** The Viscaya Channel testing the viability of winter planting in the subtropics, was 27,200 m2 extent into which 54,368 PU's of *Syringodium, Halodule* sprigs and *Thalassia* seedlings were planted. This January planting showed a low level of survival due to evidently harsh stress of winter conditions on anchored seagrass planting. This test concluded subtropical planting was a seasonally successful effort not a 12 months activity. The first planting at the Mercy Hospital site (Phase II) was 275,666 *Halodule* sprigs, and similar number of *Thalassia* seedlings into about 169,000m^2.] [*Footnote*: This latter planting was the subject of several issues occurring from two symposia organized and convened by the late RR Lewis, President of several private sector Florida companies which restored mangroves and seagrass. These symposia reports differed substantially from reports measured by the planting investigator to federal agencies, measured and reported by the planter herself. It is the only case we find in the 1786 trials of seagrass restoration (Van Katwijk et al., 2016) that a third party –not with simultaneous participation or supervision of permitting-government agency, plus with no planting investigator participation– monitored then published the data; it is also the only publication of 1786 where a 3rd party data with no agreement with planting investigator was published in gray or normal literature. The published accounts in Marine Pollution Bulletin (Thorhaug, 1985 & 1987), which cited data herein was inspected and approved by federal regulators permitting the project which indicated differing measurements and an alternative concept of success of this planting. The initial 3rd party monitoring report occurred immediately after an intense winter storm where blades detached and blew off –as is normal in a gale force storm– without the monitors excavating for remaining root/rhizome mass. This has been quoted as proof of seagrass non-sustainability (Lewis, 2015). This third party monitoring report has been quoted by Miami-Dade County environmental officials and several environmental restoration vendors. The original 3rd party report on only this site was by a monitor hired by Dade County who was a trained ornithologist using for monitoring skilled labor, undergraduate biology students all of whom were without detailed knowledge of seagrass physiology, growth, or monitoring. This ornithologist's report was never corrected over time as storm-impacted seagrasses' rhizomes regrew blades at the site. These

3rd party monitoring reports were published in the gray literature by the groups of whom (Lewis Environmental, Mangrove Systems, and the ornithologist's company) profited financially from the misinformation surrounding their erroneous long-term survival metrics. It is wisest not to include these two sites' plantings' resulting sustainability as part of this assessment in the final totals herein to avoid any controversy or complications, as this issue will be resolved elsewhere. Additionally, these two sites outcomes do not affect substantially the total data or outcome of this review.] ***e.).Central and North test plots' longevity***: Approximately 68% of the sum of planting units at each of thirteen 0.4 ha test plots (Thorhaug, 1985) have sustained over the 37 years' period with considerable expansion. (Most of the non-surviving tests plots were chosen over the objections of the restoration expert by Miami-Dade County resource management personnel, who were engineers.) Thirteen test plots originally included 52,500 PU planted (Thorhaug, 1985): western bridge abutment of 36th St Causeway on both Southwest and Northwest sides, Bird Island, northwest flats at Sabal Palm Road, 24th to 28th ST offshore, (Supplementary Fig. S-4),a site northeast of 79th St Causeway, the several dredge islands “Pace Picnic islands”, two sites at flats at northwest Virginia Key approximate to a buried sewage line, 800 m ENE of Mercy Hospital docks Fig. S-8, (and later 2000 planting about 300 m off North tip of Bay Harbor Islands' flats). The four test plot restoration sites in these two northern basins sustained well, although at the 79th St dredge island site (variables–deep and turbid), low survival occurred. There were several other plantings (Thorhaug, 1987; Thorhaug and Hixon, 1975) not herein discussed some of which included additional test plots (40,000 seedlings, 4000's *Halodule* and *Syringodium* plugs). An anthropogenic disaster occurred here. During dredging for the Port of Miami in mitigation, a dredge hole was filled in the central basin between 36th ST to 79th St, which uncontrolled fill decimated this 35 yr planting in excellent health on the North side of 36th St causeway. Some other sites there were secondary disturbances at various time periods after completed restoration, such as proximate dredging sites. The governmentally-induced changing outflow from drainage canals by State and Federal government throughout Biscayne Bay areas created changing turbidity and pollutant patterns. Hurricanes and tornados occurring in the central and North Biscayne Bay areas also effected plantings. **f.*)* Card Sound, Barnes Sound**. At another successful planting site in an estuary to the immediate south of Biscayne Bay (15,000 PU in 12,412 m^2 *Halodule wrightii* survival above 90%) (Thorhaug, 1983).The Florida Dept. Transportation built a bridge decades later on top of the restoration site (FDOT) with the causeway, on the immediate east of the plantings, removed in Lake Surprise of Barnes Sound bordered by Key Largo, Fl. g**.) Measured services of restored Biscayne Bay seagrass**: 1***.) Animals' recolonization.*** McLaughlin et al., 1983 measured the invertebrates recolonizing the Turkey Point restoration for several seasons. After 3 years of regrowth this *Thalassia* bed showed no statistical difference between restored and natural, non-impacted seagrass beds in terms of invertebrates. 2***.) Carbon.*** The supplementary Table S-1 shows a series of sites (Turkey Point, Grove Isle, 24th St.) wherein sedimentary carbon with 3 controls (naturally-occurring seagrass meadows, always-barren sediment and impacted-barren sediment) plus restored seagrass carbon were measured for sedimentary organic carbon accumulation over time as well as carbon burial rate, carbon gain and loss, and age (from date of impact plus from date of restoration to monitoring). Restored seagrass showed more organic sedimentary carbon burial than naturally-occurring seagrass sediment. A substantial amount of carbon occurred in the “always barren” non-vegetated background sediment, which control in opinion of authors needed to be subtracted from “sequestered” carbon beneath seagrass beds (Thorhaug et al., 2017).

D. **Atlantic tropical seagrass restoration examples: Jamaica** seagrass restoration results (Table 4, Fig. 4)

Jamaica is a nation in the central Caribbean Sea's Greater Antilles, independent from Britain since 1961. This first global tropical seagrass restoration training project (sponsored by US Government Agency for International Development) jointly tested and also trained methodology and species with the Jamaican Natural Resource Department and University of West Indies,Mona Botany Department. The objective was to test tolerances for restoration of near shore seagrass resources for various pollutants experienced especially in Jamaica but also as a general model to other Caribbean and Gulf of Mexico (GoM) nations. General sites of pollutant types were selected by the Natural Resource Department. The project restored 3 dominant tropical Atlantic seagrass species by 3 methods: sprigs, plugs, seedlings. Training for the seagrass restoration process were carried out with personnel from the Department of Natural Resources (Director, Beverly Miller) and University of West Indies Botany Department (Chairman, George Sidrack). Results in detail are found in Thorhaug and Miller (1984, 1986). Results were in three parts: 1.Outreach to Jamaican public; 2.) Results of test studies and a larger planting based on test studies (Table 4); and 3.) seagrass policy (written and adopted) plus training of related Caribbean Government resource management groups through UNEP, FAO, and CARICOM. Three major Jamaican public conferences were held to share information about the success of the program with the citizens, other Jamaican government and international agencies, foreign embassies, and industries. Additionally regional training sessions with Caricom government personnel sponsored through the UNEP/Caricom process were successfully held. Later FAO held Latin American seagrass training workshops were held from this data. Mitigation policies for seagrass were written in partnership with Director Beverly Miller after consulting with US agencies at State and Federal level and Caribbean nations. These policies were then adopted by the Jamaican Parliament and Prime Minister Seaga. Methods included planting at each of 19 sites with 2 species with 2 methods each of *Halodule, Thalassia,* and *Syringodium* into 0.4 m quadrats. (1800 PU in each of 19 test areas.) Results showed the best restoration methodology results in a predominance of polluted sites and control sites were by utilizing *Halodule* plugs and *Thalassia* sprigs. At low to medium levels of the majority of the common Jamaican pollutants, one or two species could tolerate them (Thorhaug et al., 1985). Measurements of blades, and laterally expanding diameters of planting units by divers (ground truth) occurred during first 18 months, then general ground observations and Google Earth Pro and other aerial imagery measurements in subsequent years. 14 or 74% of pollutant test sites sustained over 3 decades. Both seagrass growing by lateral extension (Tomlinson, 1974) and by seeding many developed into substantially larger areas (airports and port dredge and fill, around Montego Bay breakwaters, power plant outer isopleths with *Halodule*, oil spill sites with *Thalassia* and *Halodule*, and a deep site of 5 m near a river mouth at far western tip). Five other sites highly anthropogenically impacted did not survive well (cement plant with high level flocculent tailings, high salinity pond to over 75 ppt, high energy erosional sites at Hellshire with *Syringodium,* next to ship channel Ocho Rios, at entrance to Port, Montego Bay). Sufficient light appeared to be a key requirement for restoration as was medium to low energy regime, daily mean temperatures up to 29.5 °C, and salinities from 22 to 44 ppt. Working with local fishermen at Kingston Bay, at Fort Augusta Causeway site (to Portland) a larger acreage was planted near-shore proximate to a bridge over the river mouth. The results were a vibrant set of 4500 PU *Halodule wrightii* plugs planted at 1 m intervals which coalesced into a seagrass bed within 6 months and has sustained and expanded for decades despite a proximate dredge and fill on the causeway (Supplementary Fig. S-7) at which point they grew back from decimated condition after the dredge and fill operation.

E.) **Pacific Tropical/Subtropical Seagrass Restoration Examples: Indonesia Results**.

Two restored Indonesian sites are Banten Bay and Jakarta Bay on the north coast of Java. These the Sunda Straights, Lombak, and the Flores Seas were monitored for seagrass density and organic

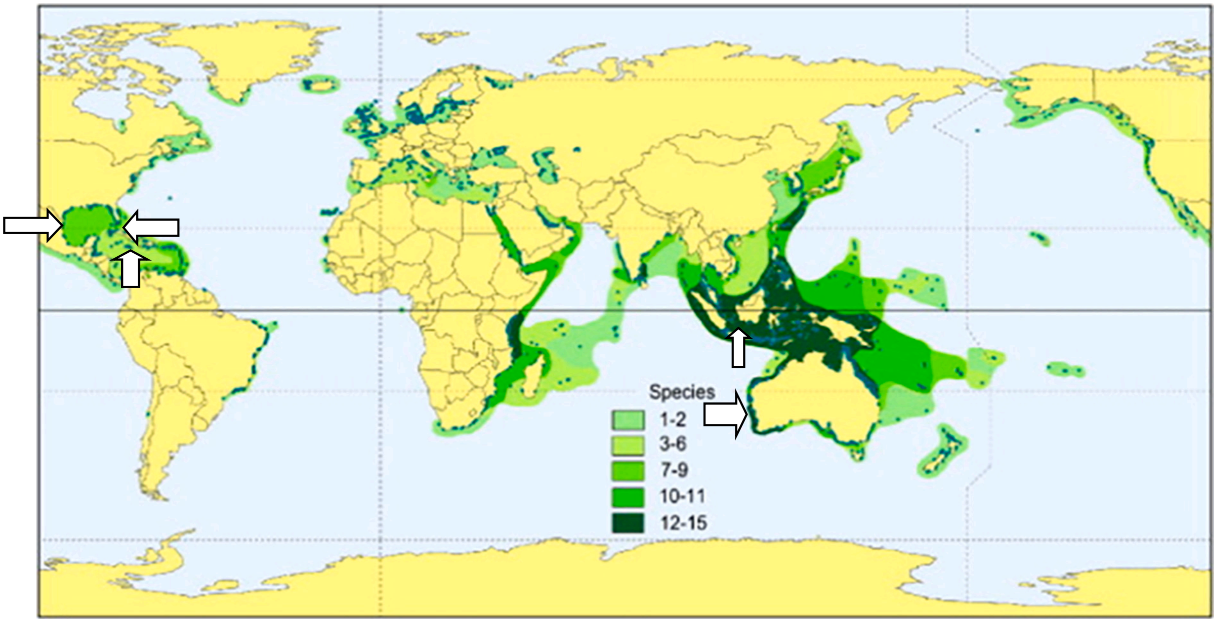


Fig. 1. Map of seagrass global distribution (basemap of seagrass from Green and Short, 2003) showing number of species in shades of green. White Arrows point to this review"s example general regions of 83 sites of sustained restored seagrass beds in Texas, Florida, Jamaica (Atlantic), Indonesia (Pacific), and Western Australia (Indian) Oceans. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

carbon.These are in the middle of the largest global tropical seagrass extent (Green and Short, 2003, Figs. 1, 5). Indonesia has about 5-6 million seagrass hectares (Green and Short , 2003 and Fortes et al 2018). As seen in Supplementary Table S-3, Kiswara created a series of restoration trials of both mixed species plantings (Kiswara, 2010a, 2010b, 2018; Kiswara et al., 2009, 2010,) and monoculture restorations including *Enhalus acoroides* and *Thalassia hemprichii*, (Kiswara, 2013) with success sustaining over a decade in Indonesia (Kiswara, 2018, Kiswara personal communication, and Thorhaug, Kiswara et al. in press in 2020). On Pari Island (North Java coast), Kiswara planted *Enhalus acoroides* by single shoots in monoculture which lasted over a decade until present (Table 4 and Supplementary Table S-3). Similarly, Kiswara's *Thalassia hemprichii* sprigs' planting, continues to grow laterally seen in repeated monitorings (Supplementary Fig.'s S-9 "restored seagrass", and S-11- "monitoring restored bed"). Sustained densities were approximately *Enhalus* 250 blades per m^2 and *Thalassia* 2500 blades per m^2. Lateral expansion rates included 20 cm/year for *Enhalus* with 50 cm/year for *Thalassia*. *Thalassia* rhizomes grew laterally at least 2.5 times more rapidly than *Enhalus* and was denser after 10 years but did not produce as much sedimentary organic carbon per hectare (Alongi, 2014; Kiswara, 2018). Table S-3 shows seagrass stock monitoring and carbon estimates from dry weight including multiple species (Kiswara, 2018) including *Thalassodendron ciliatum, Halodule pinifolio, and Cymodocea rotundata*. Similar mixed species restoration by Yap and Gallagher (2019) occurred in northeast Borneo for *Cymodocea rotundata, C. serrulata, E. acoroides, Halodule uninervis,* and *Halophila ovalis* with solid survival, however these are planted too recently to judge long-term sustainability. The *Enhalus* fruited in Java within 9 months after restoration. Generally, these species of *Enhalus* and *Thalassia* produced flowers and fruit in natural non-polluted environments, but not in polluted environments (Kiswara et al., personal communication; and Yu et al., 2019, working in tropical China). Others investigators in this region have used multiple-species plantings in one plot as examples which continue to sustain (Campulong and Philips, 1988, Thorhaug and Cruz, 1988). Still other experiments are too short term to judge sustainability (Williams et al., 2017; Yap and Gallagher, 2019, reviewed in Thorhaug et al., 2020b). Seagrass transplantation at Pari Island Jakarta Bay has been used as an attraction for marine tourism activities that are participated in by a wide variety of citizens from elementary school students to the senior citizens..

F.) Indian Ocean Subtropical/Subtemperate Seagrass Restoration Examples: Perth, Western Australia, near Cockburn Bay Results.

This coastal site in Western Australia (Table 4, Fig. 6) lies at an edge between the sub-tropical and sub-temperate zones and experiences varying shifting current patterns from the Indian Ocean. The Australian government is knowledgeable about and regulates seagrass mitigation requirements and monitors resultant products. The team of Verduin and Paling et al. carried out trial investigations in small scale to ascertain detailed methodological elements such as depth, light requirements, anchoring types, optimum energetics, species, planting technology (sods, plugs, sprigs), and environmental tolerances using nearly 8000 PU (various species) (Cambridge et al., 2006). Then results were integrated into an examination of other planting factors. Finally, the large-scale planting was executed, which planting was then monitored for multiple years, showing long-term sustainability and longevity. Since 2000 this series of restoration test results have been successfully growing into meadows (success rate = 66.3 to 90%) in large scale for the dominant species *Posidonia Australis,* particularly, of the several species attempted(Table 4). (See also Supplementary Fig. S-10.) A major planting of 120,000 anchored sprigs at depths near 2–4 m in Cockburn Sound, Western Australia (Verduin et al., In press, submitted). Verduin and van Keulen (2012) determined depths 2–4 m to be more successful for *P. australis* over 3 yr than either shallower or deeper plantings. The major results clearly demonstrate seagrass meadows surviving well over a decade. Additionally, earlier areas in the testing have sustaining seagrass results. A series of smaller plantings testing information about seagrass services have returned to the large-scale meadow: 1.) The restoration created a food-web habitat; 2.) Sediment stabilization (Verduin et al., 2012; Verduin et al., 2009; Van Keulen et al., 2010; Van Kuelen et al., 2003; Paling et al.,1999, 2000, 2001); 3.) Sequestered carbon from restored and natural seagrass has been studied by Marbà et al. (2015) in Perth, Australia seagrass plantings' carbon.

G.) Other seagrass tropical/subtropical results: There are multiple other subtropical examples which have been restored and presently persist: In Florida, (Bell et al., 1993,Knowles and Bell, 1998 rezek, 2019) in St Petersburg, Tampa Bay, plus other Tampa Bay restorations persist described by Sherwood et al. (2017). In the Florida

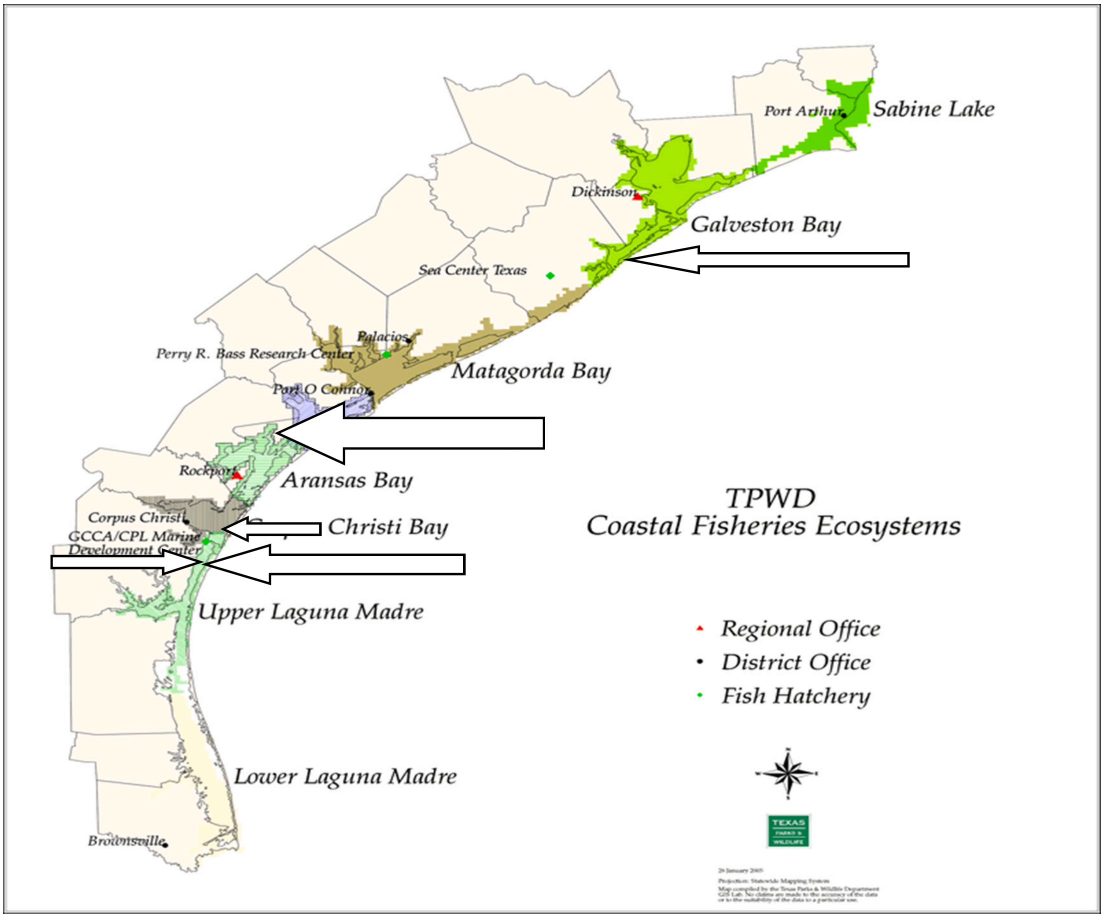


Fig. 2. Map of Texas Bays with their names (from State of Texas Parks and Wildlife Department).Arrow point to major plantings.

Keys: Key West (Hall et al., 2006Marcus and Thorhaug, 2015); at Boca Chica Key (Marcus and Thorhaug, 2015); Florida Bay west of the Florida Keys with enclosed material into boat propeller scars (Hall, 2012). In northern Florida the following persist: Apalachicola River, Fl. (Phillips et al., 1998), in St. Johns' River, Florida, (Thorhaug, 2001a, 2001b). In Mississippi, *Halodule* was restored by Eleuterius (1973), and Moncreiff (2007). In Alabama, there are test plots by Livernois et al. (2018). In Jamaica, there are further unpublished studies done for government mitigation requirements, which are persisting in Montego Bay and other areas.

4. General discussion

4.1. Global sustainability and longevity of large-scale tropical and Subtropical seagrass restoration

A.) Comparison of Restoration Longevity and Sustainability among tropical/subtropical/subtemperate Atlantic, Pacific and Indian Oceans Seagrass restorations. We delineate longevity for a series of restored seagrasses trials in three ocean basins. We provide examples within the three ocean basins at more than 83 sites planted in excess of 3 million planted units within 253 trials, extending over 300 ha (or 3 km^2). This 300 ha is a significant part of total globally restored tropical seagrass (Van Katwijk et al., 2016) which in turn was 2610 ha for the total earth , having itw mow5 significant distribution in the temperate zone. The general tropical/subtropical/subtemperate results herein (a number not previously published), demonstrate that seagrass restoration when well-executed and well-sited can sustain over many decades (Table 4).These sites provide data toward validating our hypothesis. The exceptions to sustainability occurred in sites which experienced very strong anthropogenic impacts post-planting and occasionally naturally-occurring forces during very intense storm events, especially when natural events forces occurred proximate in time to planting. However, the effects of multiple other hurricanes on the more matured restored seagrass have not diminished restored areas over the long-term in the predominance of other multiple sites. Our assembled longevity information is potentially useful to managers and scientists of seagrass and coastal resources. Generally, restored seagrass seemed to have relatively similar macro-responses to physico-chemical variables and many anthropogenic stressors among the examples.

The restored seagrasses persist for decades in these correctly-chosen sites with well-executed plantings (Table 4). There does not seem to be a large longevity difference among species. We have delineated multiple species which continue to grow laterally into available barren space beyond the perimeter of the trial plots. Obviously, each of the 253 sites in three ocean basins have their local species, spatial cover, and density optimum constrained by each sites' ambient environmental factors (especially light, depth, energetics, salinity, sediment type, and riverine turbidity input).

The Texas portion is about 6% of the calculated global restored seagrass of 26.1 km^2 by Van Katwijk et al. (2016) areas. However, the Texas restored extent of 1.54 km^2 is a far larger proportion of the *solely* tropical /subtropical restorations than of global total amount (which includes temperate and boreal), due to many fewer restoration trials in the tropics. If the discussed examples herein from Thorhaug's Florida, Caribbean and Verduin's Australian restorations were combined with Belaire's and Thorhaug/Schwarz‘s Texas restored total, then the amount is about 12% of the global tropical seagrass total restoration.

B.) Examples recapped: *Texas*.The substantial portion of the Texas estuarine plantings of 1,872,018planted units in 154.25 ha summarized

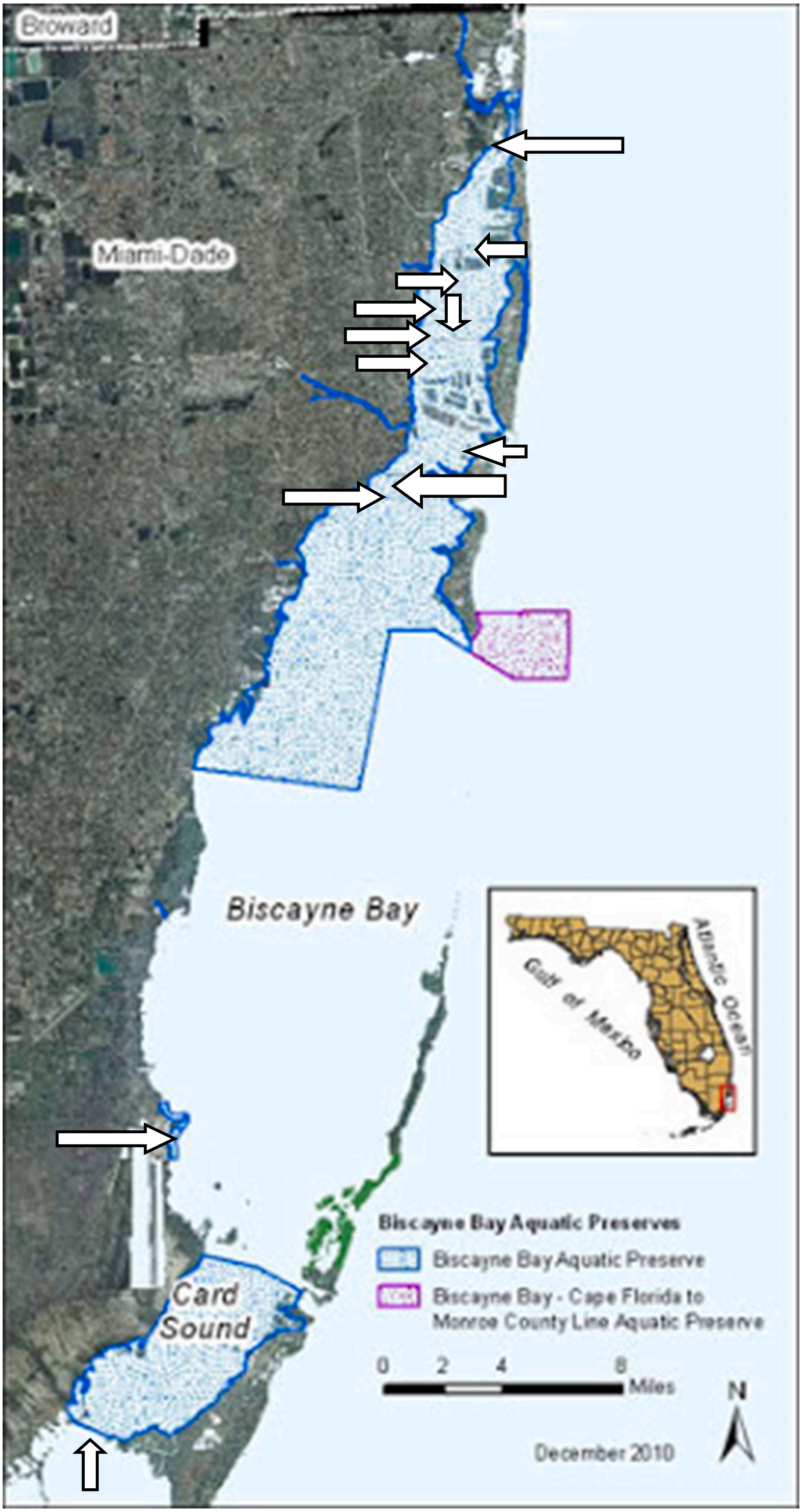

Broward
Miami-Dade
Biscayne Bay
Card Sound
Gulf of Mexico
Atlantic Ocean
Biscayne Bay Aquatic Preserves
Biscayne Bay Aquatic Preserve
Biscayne Bay - Cape Florida to Monroe County Line Aquatic Preserve
0 2 4 8 Miles
N
December 2010

Fig. 3. Biscayne Bay, Florida. From National Park, showing aquatic preserve and national park. Arrows are in regions of major seagrass restoration.

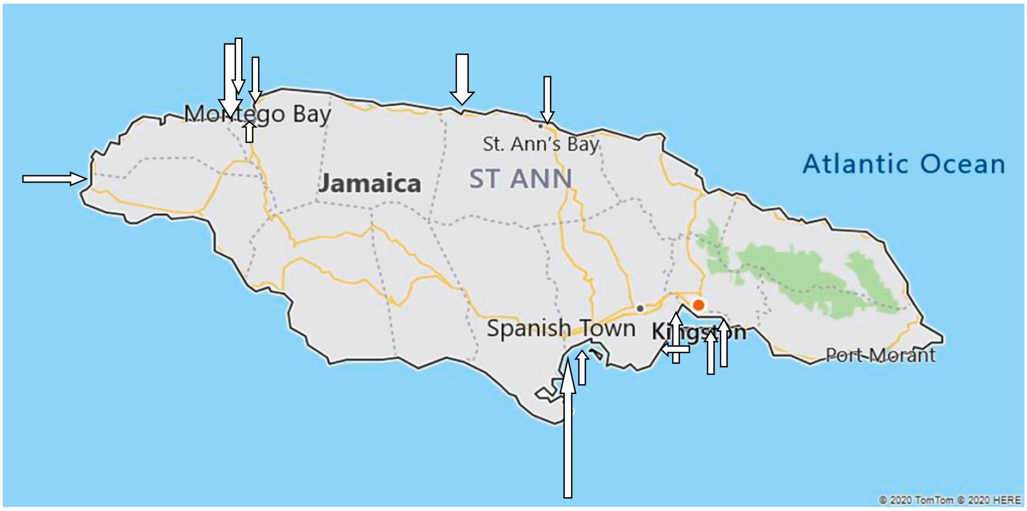


Fig. 4. Jamaica sites.

in detail in Tables 1, 2, and 3 have likewise sustained from restoration planting for up to 3.5 decades, chiefly *Halodule wrightii* and *Halophila* sp.ground cover growing laterally via rhizomal extension. These Texas plantings by Belaire, Thorhaug (2001), and Thorhaug and Schwarz (2013, 2017) were monitored in detail for 2–5 years. (State regulators inspected sites periodically; federal regulators, occasionally). After 6 years, meadows were observed for the ensuing years, including aerial photography. Together Belaire and Thorhaug/Schwarz have planted 0.99 km^2 which grew into approximately 1.3 km^2 in the Texas estuaries or about nearly 6% of the world's 26.1 km^2 restored seagrass as calculated from the 1786 global trials reviewed by Van Katwijk et al. (2016). These individual restorations (especially Thorhaug/Belaire) survived the first year approximately 65–95% remaining of the original planted units (Texas mean survival of Planted units was Thorhaug = 75.8%, Belaire = 64.5%) as inspected and certified by government scientists monitoring the restorations (monitoring after 60 d and then after 1 yr). ***South Florida:*** *Turkey Point, S. Biscayne Bay, Barnes Sound.* The oldest tropical/subtropical large-scale restoration longevity example is 47 years old, at the Turkey Point Nuclear Power Plant in Biscayne Bay, Florida carried out with *Thalassia testudinum* by 83,000 anchored seedlings (Thorhaug, 1974) in relatively shallow estuarine water, and in a medium energy regime. The Turkey Point planting was monitored for three years (including federal regulatory environmental agencies), then observed over the subsequent time period with periodic density, health, faunal composition and abundance (McLaughlin et al., 1983), and organic carbon and sediment measurements (Thorhaug et al., 2017). *North and Upper Central Biscayne Bay.* Trials numbering 71, used 1,405,200 PU into an 133 ha area. The highly urbanized and industrialized North and upper central Biscayne Bay with 50% altered shorelines (Chardon, 1976) were tested with multiple restoration sites ranging in size from 0.5 ha to 20 ha. Since in 1978–2020, these plantings have experienced a variety of post-planting impacts ranging from further dredging and filling, to powerful Atlantic hurricanes, winter storms, boat groundings, multiple sewage and oil spills.

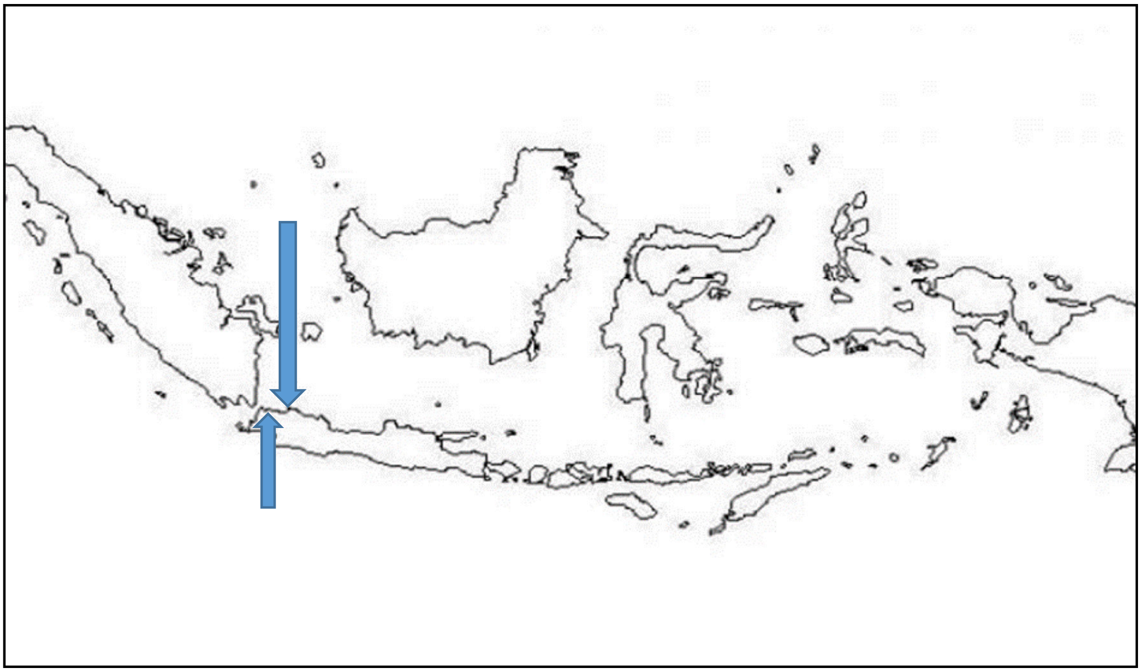


Fig. 5. Indonesia, sites of restoration as separate from monitoring of seagrass sites Monitoring only in Flores Sea, Sunda Straights, and Lombak. (base map and sites from Kiswara).

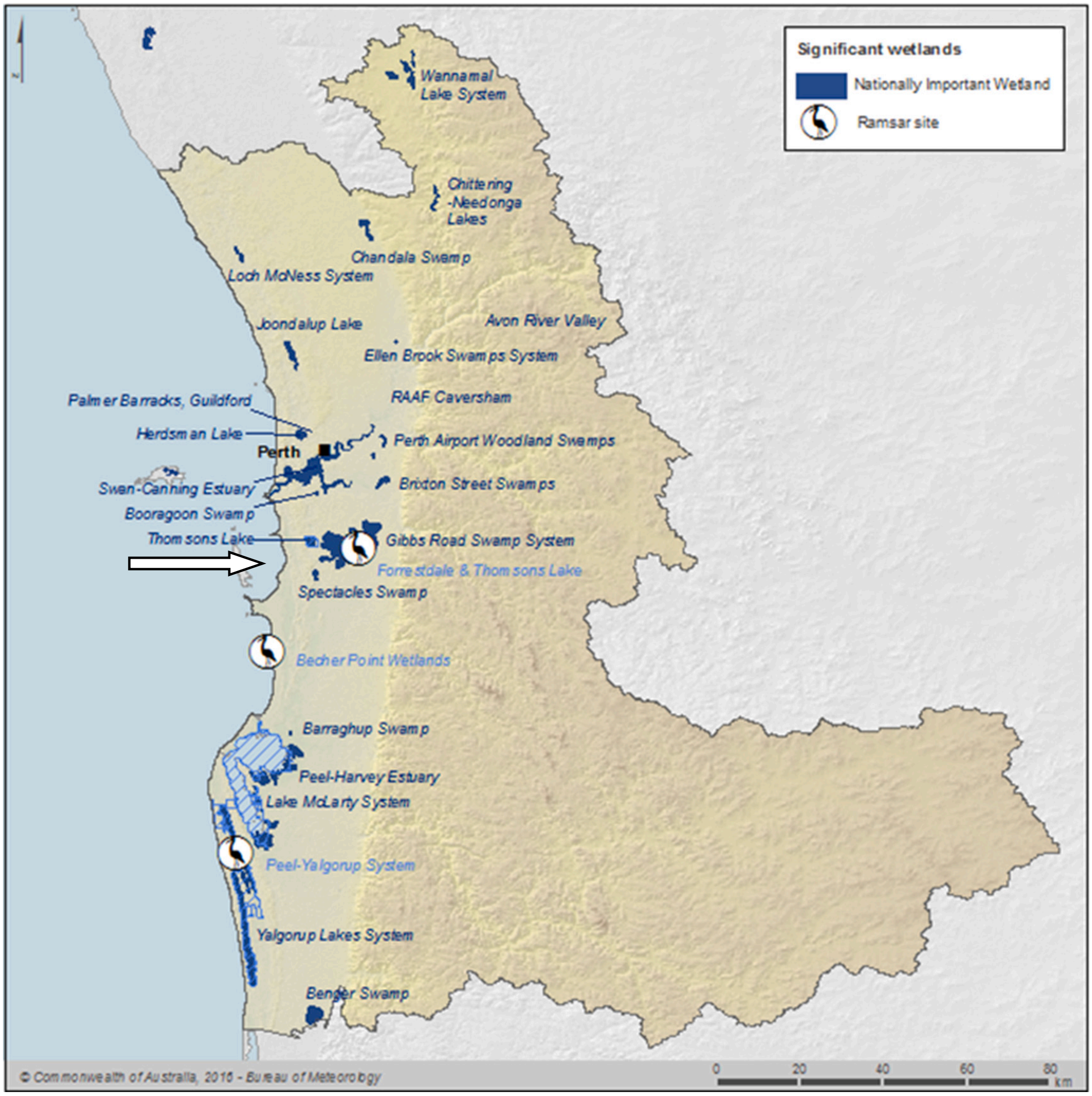


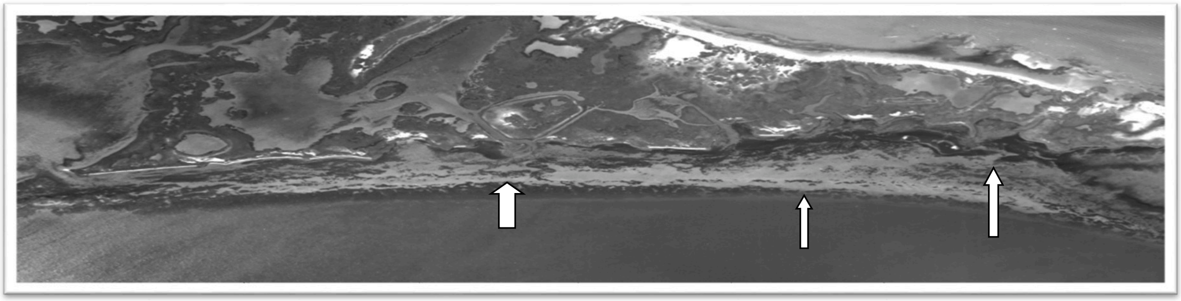
Fig. 6. Perth, Western Australia sites.

However, substantial material of the seagrass at the majority of 20 sites is still sustaining. Federal environmental regulators have inspected the plantings these Florida sites. Supplementary Table S-3 shows an example of a persistent 9.09 ha two meter deep site near a former sewage effluent outflow (McNulty, 1970) where excellent seagrass health and growth sustains. ***Jamaica***: 120 restoration trials of 3 species were monitored. One larger planting was monitored on the east side of the causeway to Portland, which experienced released fill into the adjacent area, presently has overcome its impact and remains persistent today. This and others have been re-measured during intervening years and observed through Google Earth. ***Indonesia***: 38 trials with 9 species in a series of 8 sites were planted. Various restorations were of greater success than others. Particularly Kiswara had success with single shoots of *Enhalus and* sprigs *Thalassia*. Sustainability from time planted until present. ***Western Australia:*** the restoration sustainability was measured as successful at the end of 6 years, being monitored in detail continuously, and a decade after planting continues to sustain itself in a difficult high energy environment (Verduin et al., 2012, In press; Paling et al., 2001a, 2001b). Seagrass restored into more than 3 ha with 126,369 PU.

C.) Reproduction of long-term restored seagrass: These seagrasses utilized were all perennials. Expansion of seagrass occurred due chiefly to continual lateral growth created by expansion of the rhizomes, roots, and blades. Little sexual reproduction in terms of fruiting or seeding was seen at any or near any of the disturbed areas of tropical restoration. An example lies in the Indonesian site of Pali Island, Java where restored *Enhalus acoroides* showed fruiting in the non-disturbed restored sites after 9 months, although equivalent simultaneously restored Enhalus did not have fruiting in disturbed sites (Kiswara, 2018). Another example showed *Enhalus* fruiting in a disturbed site is found on Hainan Island, China (Yu et al., 2019). *Thalassia testudinum* planted from the same genetic source plants showed some fruiting after several years in non-disturbed sites in Biscayne Bay, but not in continually disturbed sites in this estuary (Thorhaug, 1978). More investigation is clearly needed.

D.) Animal Recolonization into many seagrass restoration areas began rapidly after planting (within days in Texas and Florida). Animals increased and continued their habitat usage until a full complement of animals was found at most sites post-planting after several years (McLaughlin et al., 1983) including most of the naturally-occurring seagrass-related animals already carefully delineated at this Biscayne Bay site (Thorhaug and Roessler, 1977 which study established patterns of animal use of seagrass (both *Halodule wrightii* and *Thalassia testudinum*) in 32 sites in far south Florida monitored bi-monthly over 7 years. In Bell et al.'s (1993) and Knowles and Bell's (1998) study in Tampa Bay of various-sized small restorations, these authors noted size

The original 1988 Area Prior to Restoration of 17.24ha (172,402.2 m²) (Photo by Langmon)



After Restoration with *Halodule wrightii* bare root plugs in 2009 (photo by Langmon).

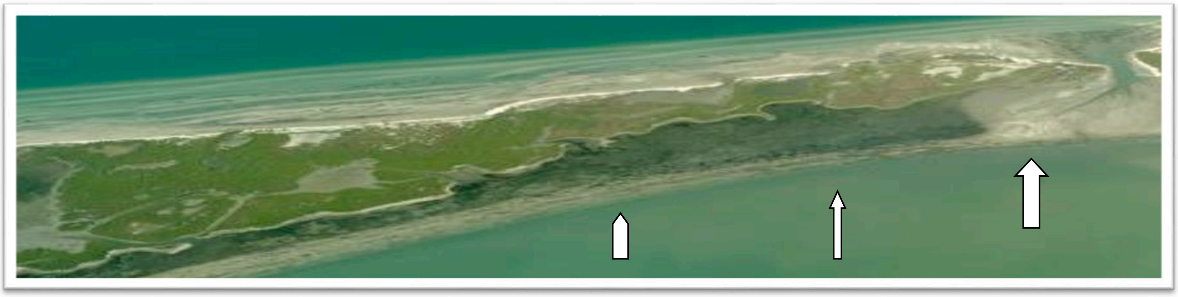
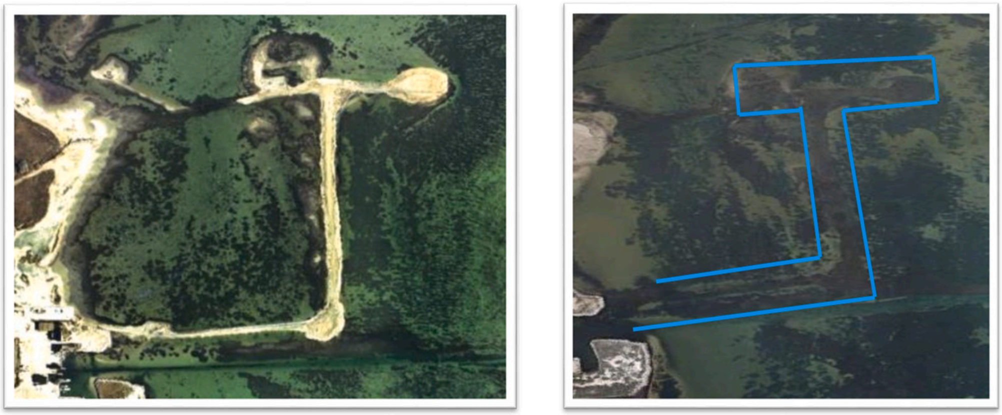


Fig. 7. Mud Island Laguna Madre seagrass before(above) restoration and after (below) 1989 restoration by Belaire. 17.24 ha (172,402.2 m^2). Restoration area planted with *Halodule wrightii* bare root plugs in 1989.

of planted areas affected animal recolonization. In Texas, Stunz et al. (2002), Levin and Stunz (2005) measured a significant animal use of naturally-occurring seagrass habitat. Livernois, Heck et al. (2018) have examined animals in Alabama in restored and natural seagrass. No such quantitative animal studies in restoration sites have been done in the Indo-Pacific. After disturbances (major hurricanes with months of sustained low estuarine salinities), key fisheries' animals had recolonized into Texas restored sites within 3 months (Thorhaug, 2017). Endangered species found these seagrass restorations within weeks of planting usually using the seagrasses' food web as food sources (manatees or dugongs, Whooping Cranes, Great Blue Herons, White Pelicans, various sea turtles, etc.) (Thorhaug, 1985, 1987, 2001a, 2001b, 2014).

E.) Sediment Resilience & Stability of restored Seagrass Shoaling. A series of restoration trials have shown stabilization and building of sediment at restored sites. Stability of long-shore seagrass restorations in Texas were able to sustain through hurricanes and tropical storms at Galveston Bay San Luis Pass, Aransas/St. Charles Bays at Lamar, Croaker Hole in Corpus Christi Bay, and Predator Island north shoreline in Laguna Madre (Thorhaug, 2017). Resilience was also seen in Turkey Point, Florida and multiple impacted urbanized sites in North Biscayne Bay, FL. Resilience was clear in Western Australian sites of Verduin et al. (2011).

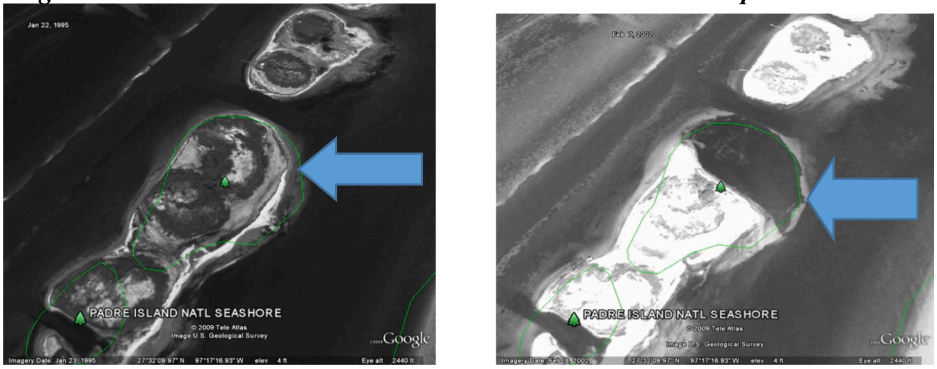
F.) Carbon was sequestered from restored seagrasses in Florida and Texas from their early months after restoration onward (Thorhaug et al., 2017) (See Table S-1 in Supplementary Materials for carbon at multiple longevity sites). Blades and detritus began entering the sediment within a month of restoration planting. In the Gulf of Mexico, the two major states with seagrasses are Texas with 94,389 ha and Florida with 850,974 ha. Southeast Asia seagrass extends to more than 6 million hectares (Alongi, 2014, Fortes et al 2018) which comparatively is six times greater in seagrass extent in the Gulf of Mexico due to a large coastal shallow Asian area with extensive shorelines and off-shore islands. Thorhaug et al. (2017) sampled a series of Thorhaug's restored



Before planting and scrape down in 1989 (left).

Post-planting in 2001 sustained bed(right).

Fig. 8. North Laguna Madre, old oil causeway scrape down. Before(left) and after (right) 1995 Belaire scrape down and planting of 27 ha (27,314 m^2 restoration Area. Planted 1995 by *Halodule wrightii* bare root plugs. Belaire, 1995). Before planting and scrape down in 1989 (left). Post-planting in 2001 sustained bed(right).



1997 prior to scrape down of sediment *wrightii* at north end of Predator Island.

2009. Restoration 1999, 60,000 *Halodule mixed w/ Halophila*. Coalescence in 3 mo.

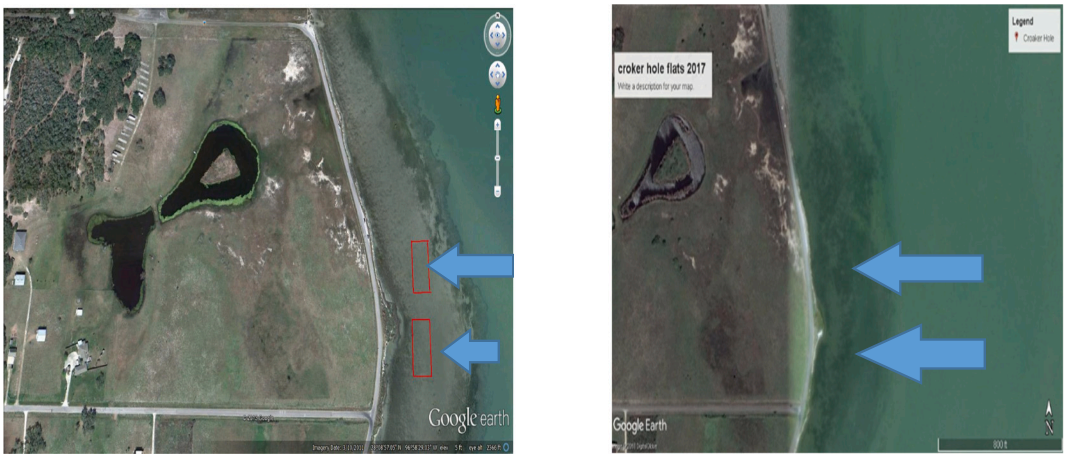
Jan 22, 1995
PADRE ISLAND NATL SEASHORE
© 2009 Tele Atlas
Image U.S. Geological Survey
Google
Feb 1, 2002
PADRE ISLAND NATL SEASHORE
© 2009 Tele Atlas
Image U.S. Geological Survey
Google

Fig. 9. Predator Island North Laguna Madre, a 1949 spoil Island of USAEC. Before (left) and after (right) scrape down (1998) and Thorhaug 1999 planting. 5.9 ha planted Thorhaug (2001).

seagrass around the Gulf of Mexico finding large amounts of carbon post-restoration (Supplementary Fig. S-1). Natural seagrass carbon was 25.7 ± 6.7 MgC_{org}ha^{-1}. Restored seagrass carbon was a mean of 38.7 ± 13.1 Mg C_{org} ha^{-1}. Greiner et al. (2013) found substantial carbon under restored *Zostera marina* beds in Chesapeake Bay, FL. No data is yet available on carbon exudates in months after restoration versus accumulation from detritus. Carbon from restored sites was also measured in Perth, Australia where the Verduin and Paling et al. restoration work occurred (Marbà et al., 2015).

G.) Methodological Successes. Manual planting of plugs and sprigs gives adequate and reliable results in 83 Texas, Florida, Jamaica, Indonesia, and Australian sites. In Texas plugs and sprigs do not necessitate either anchors or fertilizers. Sprigs were not used in large scale planting for Texas nor have seeding methodologies ever been carried out in large scale for *Halodule, Halophila, Syringodium, Thalassia* or *Ruppia* in Texas. In South Florida, *Thalassia* seeding restoration has been successful in far southeast Florida in Biscayne Bay/Card Sound which flushes into the Gulf of Mexico and Atlantic (Thorhaug, 1974, 1978, 1981, 1995) as has *Thalassia* planted on large scale from sprigs and plugs (Thorhaug, 1978, 2000, 2012). *Syringodium* has been planted by plug and shoot in large scale in Florida, Texas, Jamaica, and other areas with less PU survival success than *Halodule wrightii* (Belaire, Table 2 and Thorhaug, 1983, 1987, 2012**)**.

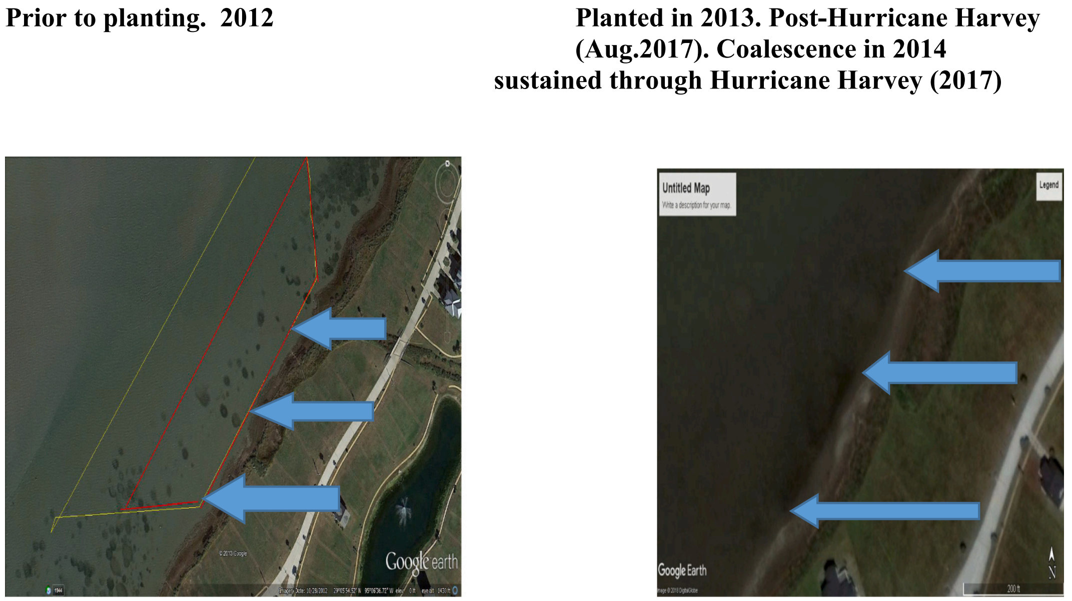
H.) Government Policies and Regulatory Standards for Seagrass Restoration. The government resource management policies (federal, state and local) for maintaining seagrass through mitigative restoration for "taking" of seagrasses put into place in the 1970–1980's globally are not creating sufficient seagrass stock to alleviate the decimation (Fortes et al., 2018; Waycott et al., 2009) created by the past 20th Century and earlier losses. This is clear in the Texas, Florida, Jamaica, Australia, and Indonesia examples. Nor is natural seagrass recolonization sufficient to regenerate the seagrass extent degraded due to present anthropogenic activities. Thus, we call upon Government and Private Sector working together to initiate a major efforts to revitalize seagrass extent by restoration filling in tropical/subtropical areas barren from past impact. New policies need to be put into effect to rebuild the seagrass beds. In Texas, this is being conceptually handled by the Texas General Land Office Coastal Master Plan adopted by the Texas legislature. In the Philippines, there is a Seagrass Plan for the nation (Fortes et al., 2018). In the Texas restoration example, the present restored seagrass quantity described herein only comprises four ten thousandths of that seagrass estuarine-bottom-land which has been decimated of seagrass. New policies are also needed throughout the Greater Gulf of Mexico and Caribbean Sea because accelerating loss of seagrass from increasing turbidity {example, Mississippi River turbidity, and six rivers in Puerto Rican (Thorhaug et al. 2016)], plus other anthropogenic disturbances



Prior to restoration, photo taken in 2011. Planting in late summer/fall 2013

Post-restoration and 3 months after Hurricane Harvey 2017, 4 years post-planting.

Fig. 10. Aransas/St. Charles Bay near Big Tree, Lamar, TX. Before (left) and after (right) Thorhaug/Schwarz 2013 restoration.


Prior to planting. 2012

Planted in 2013. Post-Hurricane Harvey (Aug.2017). Coalescence in 2014 sustained through Hurricane Harvey (2017)

Fig. 11. Galveston Bay at San Luis Pass (from Thorhaug, 2016, 2017).Before (left) and after(right) Thorhaug/Schwarz 2013 planting.

such as the Deepwater Horizon and other oil spills, are continually occurring despite Federal and State governments' ongoing conservation measures protecting and preserving certain areas. The greatest problem in Texas appears to be open water dumping and "enrichment" carried out by the US Army Corp of Engineers with dredge spoil (releasing large amounts of unconsolidated particles into the water) which activity is very negative to the light requirement for seagrass sustainability. Government policy created mistakes in the past for which we presently need the following corrections: 1.) Government at State, Provincial and/or National levels should take a holistic view of lost resources and have a master plan to increase badly damage resources over a decades' time with a master plan for funding to move forward as has the Chesapeake Bay seagrass restoration program; 2.) In the USA and parallel nations,the US Army Corps of Engineers policy should be reexamined for adding fill to any area where these particles might enter riverine or estuarine waters diminishing light for seagrasses; 3) In terms of present regulations and policy, It is essential that the seagrass restoration experts should choose the exact site for seagrass restoration, rather than government regulators, engineers, or for the company mitigating employees or attorneys.

I.) Government Specifications for Restoration Success Needing Adjustment. The criteria to judge "success" should be a percentage comparison to proximate naturally-occurring seagrass areal extent cover per hectare based on measurements of equivalent naturally-occurring seagrass meadows (proximate, same energy environment, same depth, same species, same bottom type). We reject the government criteria that a fixed proportion of the planted units should be the measure of success as an adequate regulatory standard. Natural seagrass density and extent differ widely within estuaries so that the coverage & density of the area is the only relevant metric, whereas the presently "fixed standard" is inadequate. Timing of measurement is also important. Some seagrass (*Halodule, Syringodium, Halophila*) grow very rapidly, while others (*Enhalus, Thalassia, Cymodocea, Amphibolis* etc.) take years to grow into 9 m2. Care should be taken to do assessment measurements of these seagrass parameters in middle to late spring or early fall, not winter (winter is when winds may have blown most blades away), and similarly not during hot periods in the summer, or within 3–4 months after hurricanes or intense tropical storms. Additionally, when restored sites have various depths, then these equivalent controls standards should be used for each 0.5 m depth (Dunton, 1994; Onuf, 1996) where density and extent are likely to vary.

Tropical and subtropical seagrass restoration is adequate in terms of technical methodologies to be scaled-up in many tropical areas, showing results of large scale successful plantings, sustainability, and long-term services to the public to enter the globally applied remediation and preservation programs nationally along with ongoing marsh and mangrove restoration, which has previously been scaled up successfully in many nations.

J.) Engineered Seagrass Restoration Projects. We have presented a series of normal revegetation plantings on barren sites. However, several "engineered" solutions were included within the Texas examples. The engineered seagrass solutions cost substantially more per hectare of final surviving seagrass and services. The key question is, "Would the ecosystem have benefited by further seagrass plantings (which would create at no additional cost to the restoration much additional carbon sequestration, fisheries ecosystems, and shoreline resilience, water clarity and other services), rather than the sponsor investing the same money in the pure engineering solutions resulting in less seagrass, but engineered structures?" (This includes monies invested for engineering designs, excavations, equipment, and the time involved by attorneys and administrators in coming to engineering decisions plus the cost of any negative side effects.) The government does not provide quantitative documentation for judging the cost effectiveness of the services from engineered projects so "hear say" of expenditures can only be estimated, but engineering is usually extremely high cost versus planting additional seagrass. Engineering side effects normally include seagrass disruptions due to loose sediments creating a turbidity increase, dredge and fill, or current changes or increased sediment transport away from the shorelines.

K.) Opportunities for Further Restoration. In the tropics and subtropics huge seagrass areas of barren or slightly vegetated bottom sites exist from decimation of previous seagrass beds. These barren areas could be utilized to restore the previous large losses of seagrass. Additionally, clearly seen in Predator Island, Laguna Madre (Thorhaug, 2001a, 2001b) and several Belaire sites in Laguna Madre and Corpus Christi Bay, scrape-down of previously-dredged-up land could also provide successful seagrass restoration opportunities. As one example, each assessment of each Texas estuaries' seagrass has been made for prior and present seagrasses (Pulich, 1998) plus a Galveston Bay historical seagrass mapping study by the Houston Advanced Research Center of seagrass from the 1950's until 2000's. This mapping historically to the present also has occurred in Florida (Yarbro and Carlson, 2011; Chardon, 1976), in Louisiana by Poirrier and Handley (2007), in Mississippi by Moncreiff (2007), and in Alabama by Heck et al. (2015). This level of extent and former seagrass mapping has not yet occurred in many tropical nations and is needed. Studies of sites where seagrass can successfully be returned must be assessed by experts in seagrass restoration, not simply seagrass researchers or general marine ecologists. This is because the assessment is very difficult, integrating multiple factors critical to success. Seagrass expertise is in a far earlier stage of science after 4 decades than is marsh or mangrove restoration, which have been carried out for a millennium or more. Seagrasses are scientifically far more difficult to restore than marshes or mangroves due to the plants being totally submerged in ambient water quality rather than diurnally exposed to sunlight and the atmosphere. This includes being exposed to pressures caused by water energetics. However, this report, the report of Van Katwijk et al. (2016), and other summary reports show seagrasses can be restored successfully to bring back the various services to citizens such as stabilization of the nearshore bottom sediment, productivity for fish and shellfish nurseries, carbon sequestration, and the food web for endangered species and migratory bird routes. In some cases marsh or mangroves plus seagrass habitats' tandem restoration attempts can be optimal, such as planting of marsh or mangrove along the shoreline and seagrass from low tide outward into the estuary (in waters clear enough for seagrass growth and which previously contained seagrass).

5. Conclusions

A.) **Multiple seagrass restoration results from five tropical/subtropical/subtemperate portions of three ocean basins at 83 various sites and over three million units planted into over 306.3 ha demonstrate longevity up to 47 years in well-restored, well-sited seagrass.** This includes approximately 12% of the total tropical restored seagrass globally as calculated from the review of Van Katwijk et al. (2016) or 6% of all restored seagrass in all zones. Although most sites discussed restorations living sustainably for 18 months after planting then remained stable until the present, in a few cases heavy anthropogenic impacts occurred in the various estuaries, which degraded a few of the individual restoration sites. Several severe wind events disrupted a few of the 83 restored sites, although most restored areas sustained through very intense wind events. In Texas, over 163.8 ha with a million and a half planted units almost all projects persisted since date of planting, except several with very harsh anthropogenic impacts.

B.) **This review creates clearly a demonstration of many decades' longevity of tropical/subtropical seagrass restoration** when expertly planted in a well-chosen site. This review may help provide an informational background for government resource managers, legislators, scientists, and citizens about tropical/subtropical seagrass longevity to substantiate future investments in seagrass restoration efforts, using these long-observed projects as examples. Both the older examples in Florida, Texas, and Jamaica, along with more recent examples in Australia and Indonesia show longevity since the planting inception. Some of the genuses are similar between restoration efforts in the Atlantic (Van Katwijk et al., 2016) and Pacific tropics/subtropics (Thorhaug et al., 2020b) such as genuses of *Halodule, Thalassia, Syringodium, Halophila, Ruppia.* This allows successful techniques to be replicated with some reliability within a genus between oceans basins. Other species are unique to a specific ocean such as the Indo-Pacific (*Enhalus acorides, Posidonia australis*). We note that seed plantings appear difficult in the tropics, although cultured seedlings show some success. However, services of the persistent restored seagrasses have not been compared between the several basins. Despite indications of services from excellent individual investigations of tropical/subtropical animals recolonizing seagrass restorations in the Atlantic (McLaughlin et al., 1983; Bell et al., 1993; Knowles and Bell, 1998; Sheridan, 1997; Heck et al., 2011; Heck et al., 2015; Livernois et al., 2018), of sedimentary carbon sequestered in restoration studies (Marbà et al., 2015; Thorhaug et al., 2017), and of nearshore resilience (Thorhaug et al., 2017), the longevity of seagrass services have not yet been formulated into data sets.

C.) **In terms of policies and government and private sector actions**, the missing element in restoring and thus returning the valuable seagrass resources to the citizens is political will for funding seagrass projects. Seagrasses have generally been subject to an irrational bias in favor of marshes, mangroves, or coral reefs in terms of funding and setting aside Ecosystem Preserves. Seagrasses offer equivalent, valuable sets of services compared to those of mangroves, marshes while frequently forming an important link between the shoreline habitats of mangrove habitats and corals in the tropics and subtropics.

D.) ***Seagrass Tolerances for ambient levels of water pollutants.*** We note restored seagrass tolerate some low to intermediate levels of various pollutants, however, massive pollutants or severe short-term disturbances are not well-tolerated. These tolerances are somewhat dependent on pollutant type. Thus, judging from this data set, we recommend small test plots to test “light” regime periodic duration, “energetic” extremes, tolerance to pollutant load, and “substrate stability” prior to a large-scale project (See Verduin et al., 2011; Paling et al., 2009 a, b, c or Thorhaug, 1985, 2001, 2017 and Thorhaug et al., 1985). **E**xamples of tolerance to pollution [previously studied levels of sewage by Satschi et al., 2001, petroleum products, other refinery effluents in sediment by Benoit et al., 1994, levels of herbicides, and pesticides] are seen in both natural and restored *Halodule wrightii,* and *Halophila engelmanii* from Corpus Christi Bay northward to southern Galveston Bay. Turbidity tolerance is seen in Biscayne Bay, Florida (Thorhaug, 1976) for *Thalassia* and *Halodule* and limits for *Halodule* in Laguna Madre (Dunton, 1994; Onuf, 1994). Frequently, investigators are required to restore seagrass in less than pristine Bays. The potential restoration application to a series of pollutants was the purpose of knowledge acquisition by large test plots in Jamaica under pollution conditions from sewage, dredge and fill, mining, water current diversion, low and high salinity, oil spill, heated effluents, and urban run-off (Thorhaug et al., 1985) and in Philippines (Thorhaug and Cruz, 1988) where dredge and fill, sewage, thermal pollutants, chemical effluents, mine tailings, and other pollutants were tested. The selected tolerant seagrass species restorations appeared sufficiently tolerant to sustain meadows over decades in these impacted bays. It should be noted seagrasses appear to have particularly low tolerance to turbidity created by dredging and filling, riverine outflows of both particulate turbidity from soil erosion plus agricultural over-fertilization (Onuf, 1994, 1996, Thorhaug et al., 2016.).

CRediT authorship contribution statement

The Texas projects reported in results were designed by C. Belaire and A. Thorhaug (each project separately designed by one or the other investigator). Execution of planting included C. Belaire for those so denoted and A. Thorhaug, A. Oerke for 1993–2000 and A. Thorhaug with A. Schwarz during 2013–2018 for those denoted “Thorhaug”. The earlier reports of Biscayne Bay, Card Sound, Barnes Sound, Florida by Thorhaug, and Jamaica by Thorhaug and Miller et al., and others were supervised and published by Thorhaug. Monitoring included C. Belaire for all his projects, and A. Thorhaug & A. Schwarz for the series of Laguna to Galveston projects with federal monitors also inspecting Laguna sites and state monitors each site. The data was furnished for Australia by JJ Verduin, for Indonesia by W. Kiswara. The tables and basic data were assembled by C. Belaire and A. Thorhaug, and A. Schwarz respectively. The manuscript was assembled and written by A. Thorhaug with all interpretation of Belaire data by Belaire. Editing was done by C. Belaire, and A. Schwarz. The illustrations were assembled by

C. Belaire and A. Thorhaug with contributions from Verduin, Kiswara, Yap, and Schwarz.

Declaration of competing interest

None of the authors has financial or other relationships which will mean that there is conflict of interest with the results. No author has financial interests in any part of this

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2020.111544.

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